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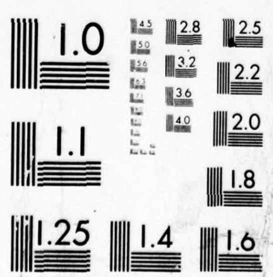

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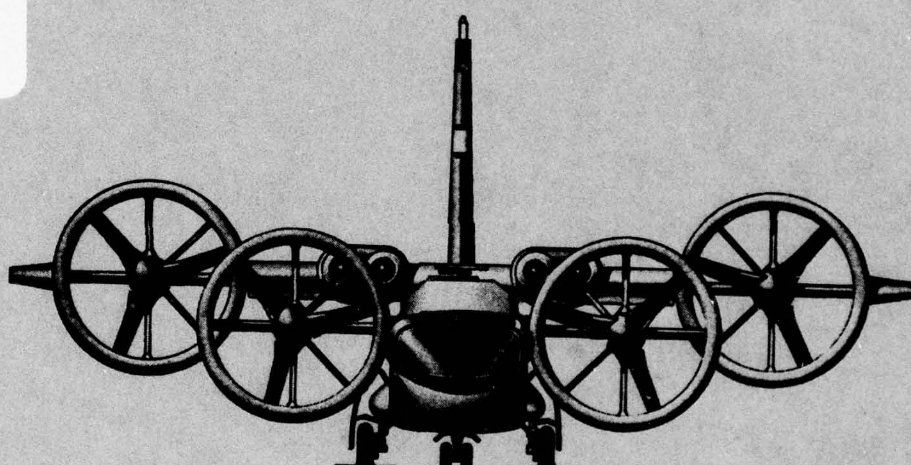
AN EXPERIMENTAL INVESTIGATION OF CONTROL-DISPLAY REQUIREMENTS FOR A JET-LIFT VTOL AIRCRAFT IN THE TERMINAL AREA

Final Report
July 1978

by

J. V. Lebacqz
R. C. Radford
J. L. Beilman



Prepared Under Contract N62269-76-C-0370
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The fourth flight research program using the variable stability, variable display X-22A VTOL research aircraft was undertaken with the objective of expanding the operational capability of VTOL aircraft under adverse weather conditions. The experiment investigated a matrix of control, display and task variables for the landing approach task in a ground simulation phase followed by an in-flight simulation phase. Aerodynamic characteristics of the McDonnell-Douglas AV-8B Advanced → over

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19. KEY WORDS (Cont.)

VTOL Aircraft Flying Qualities
VTOL Flight Test
VTOL Stability and Control Augmentation Systems

20. ABSTRACT (Cont.)

Harrier were simulated for a prescribed decelerating approach profile using the X-22A's variable stability system; around this simulation, an analog of the AV-8B control system was implemented to investigate a range of realizable control system designs. Combinations of these control concepts and a variety of head-up display formats and information levels were evaluated in flight for simulated instrument approaches. A total of forty-three in-flight evaluations were obtained for twenty-two different configurations selected from a matrix of six flight control schemes and seven head-up-display formats. The flight control schemes included simple rate-SAS, rate-command-attitude-hold and attitude-command-attitude-hold systems. The display presentations were comprised of two basic formats, each of which provided orientation, airspeed, altitude and range to touchdown. Variations on the basic formats involved display of velocity, velocity commands, control-directors and horizontal-situation information. Although the previously (Task III) demonstrated trend of improved pilot rating with increased display information was not evident, one result of the experiment was that none of the display formats produced consistently satisfactory pilot ratings for the instrument landing approach to hover task when used in combination with the proposed AV-8B rate SAS. However, with more complex flight-control schemes, i.e. rate-command attitude-hold (as currently planned for the AV-8B) or attitude-command-attitude-hold, satisfactory pilot ratings were obtained with a variety of display formats.

FOREWORD

This report was prepared for the United States Naval Air Development Center at Warminster, Pennsylvania under contract No. N62269-76-C-0370 by the Calspan Corporation, Buffalo, New York. It documents the X-22A Flight Research Program performed under that contract during the period July 1976 to August 1978.

The flying qualities research experiment reported herein was performed by the Flight Research Branch of the Flight Sciences Department of Calspan. Mr. J. L. Beilman was the Program Manager. Dr. J. V. Lebacqz was the Project Engineer and Mr. R. C. Radford was the Aeronautical Research Engineer. Mr. E. W. Aiken was the Aeronautical Research Engineer during the initial phase of the program. Mr. R. D. Till was the Project Engineer for the electronic systems, both airborne and ground-based.

Contract administration and technical monitoring was performed by the Naval Air Development Center. The authors wish to acknowledge the support provided for the program by Mr. R. F. Siewert of the Naval Air Systems Command and Messrs J. W. Clark, Jr. and C. Mazza of NADC. The authors also wish to acknowledge the efforts of the U. S. Marine Corps test pilots, Captains J. Anderson and B. O'Connor, in assessing the fidelity of the X-22A in-flight simulation of the AV-8A/B type airplanes. The authors appreciate the assistance provided by both Chief Warrant Officer W. Bellis of the New York Air National Guard and Mr. E. Hetherly in flying the chase helicopter during the flight tests of the X-22A.

Research programs using the X-22A aircraft require extensive efforts and contributions from a large number of individuals at Calspan. The authors are particularly grateful to: Mr. N. L. Infanti, Calspan Chief Pilot who was the safety pilot, and Mr. Rogers E. Smith, evaluation pilot, for their efforts in the conduct of the flights under frequently trying circumstances; Mr. R. D. Till, Mr. T. J. Gavin, and Mr. C. L. Mesiah for the design, installation and programming of the programmable HUD system; Mr. W. Close for the mechanical design of the HUD installation; and Mr. J. Lyons who was responsible for the extensive data processing required for this program. The authors are also grateful for the outstanding efforts of the individuals responsible for maintenance of the X-22A airplane (Messrs D. Dobmeier, H. Chmura, G. Ewers, W. Wilcox) and electrical fabrication and maintenance of the X-22A systems as well as operation of the microwave landing system (Messrs D. Begier, T. Franclemont and J. Shattuck). Finally, special thanks are given to Mses D. Thurn, M. Ford, J. Cornell and D. Kantorski for their assistance in the preparation of this report.

ABSTRACT

The fourth flight research program using the variable stability, variable display X-22A VTOL research aircraft was undertaken with the objective of expanding the operational capability of VTOL aircraft under adverse weather conditions. The experiment investigated a matrix of control, display and task variables for the landing approach task in a ground simulation phase followed by an in-flight simulation phase. Aerodynamic characteristics of the McDonnell-Douglas AV-8B Advanced Harrier were simulated for a prescribed decelerating approach profile using the X-22A's variable stability system; around this simulation, an analog of the AV-8B control system was implemented to investigate a range of realizable control system designs. Combinations of these control concepts and a variety of head-up display formats and information levels were evaluated in flight for simulated instrument approaches. A total of forty-three in-flight evaluations were obtained for twenty-two different configurations selected from a matrix of six flight control schemes and seven head-up-display formats. The flight control schemes included simple rate-SAS, rate-command-attitude-hold and attitude-command-attitude-hold systems. The display presentations were comprised of two basic formats, each of which provided orientation, airspeed, altitude and range to touchdown. Variations on the basic formats involved display of velocity, velocity commands, control-directors and horizontal-situation information. Although the previously (Task III) demonstrated trend of improved pilot rating with increased display information was not evident, one result of the experiment was that none of the display formats produced consistently satisfactory pilot ratings for the instrument landing approach to hover task when used in combination with the proposed AV-8B rate SAS. However, with more complex flight-control schemes, i.e. rate-command attitude-hold (as currently planned for the AV-8B) or attitude-command-attitude-hold, satisfactory pilot ratings were obtained with a variety of display formats.

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Section 1
INTRODUCTION AND SUMMARY

A fundamental problem that must be addressed in the development of operational VTOL aircraft is a requirement to perform decelerating transitions in the terminal area under instrument meteorological conditions. If the aircraft is limited to operating in weather which permits visual transition to hover, a considerable degree of operational flexibility is lost; it has been estimated that the AV-8A Harrier weather minima for VTOL operation (400 feet ceiling, approximately 1 nm visibility), which are a result of requiring transitions in VMC, preclude operations from European land bases one-third of the time. The AV-8B design goal of 100 ft. ceiling/0.25 NM visibility will substantially increase such operations. The NAVTOLAND project goal of zero ceiling, 700 feet visibility operations would show an 89 percent improvement in operational readiness (Reference 1). To achieve an instrument transition capability, it is clear that particular attention must be paid to the aircraft control characteristics in this flight regime and to the type of information that must be displayed to the pilot, because the requirement to control a nonconstant total velocity and the generally poor flying qualities of VTOL aircraft during the transition from aerodynamic to powered lift result in a pilot workload considerably higher than for instrument approaches in conventional (CTOL) aircraft.

In an experiment conducted with the U.S. Navy variable stability, variable display X-22A V/STOL aircraft in 1975, the effect of generic levels of control and display parameters on instrument decelerating approaches for VTOL aircraft was investigated in flight for the first time (Reference 2). This program demonstrated two major points:

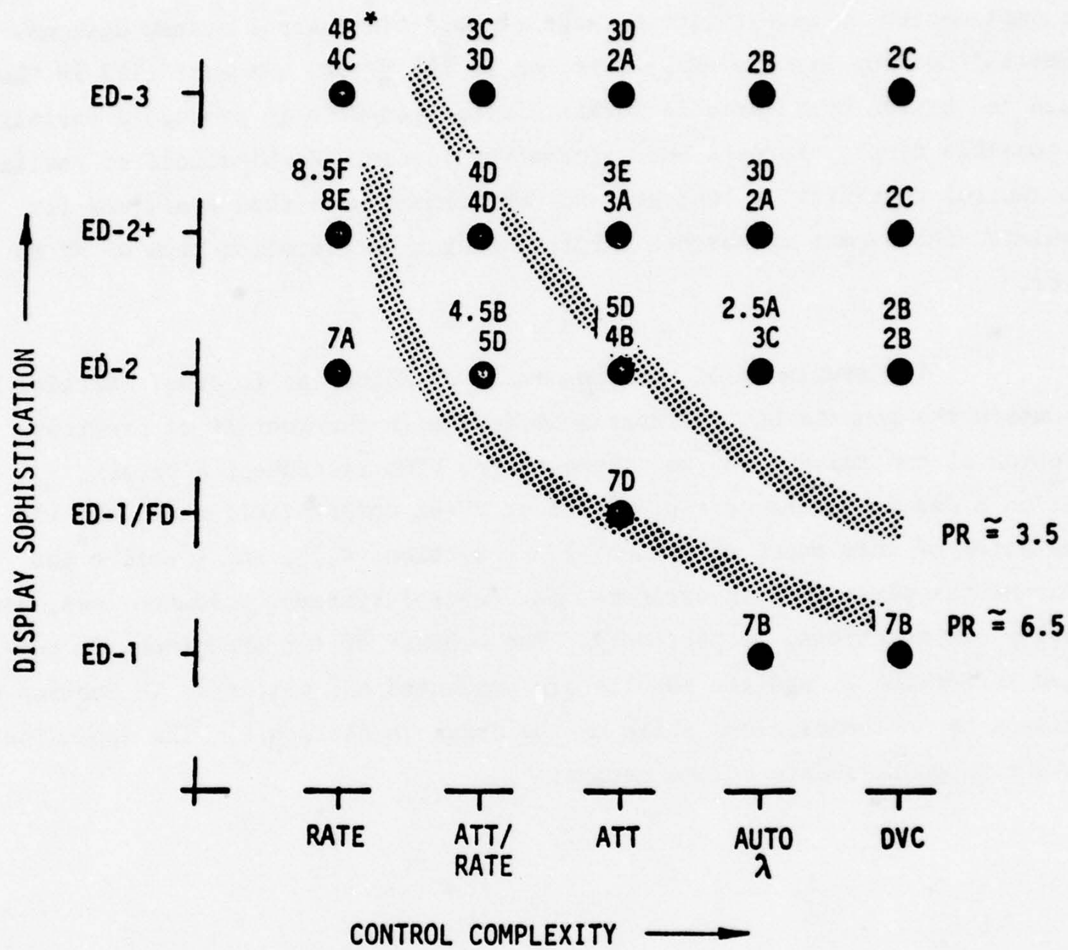
- Descending decelerating approach transitions from forward flight to hover may be performed by VTOL aircraft under instrument conditions given satisfactory control and display system characteristics as defined in the experiment.

- A trade-off between control augmentation complexity and display presentation sophistication exists for generic levels of each.

The major results of the experiment on which these points are based are shown in Figure 1-1. It can be noted that increasing control system complexity reduces the influence of displayed information level on pilot rating; for the simpler control concepts, such as rate-damping-only, sophisticated flight director displays are required to achieve an acceptable control-display combination.

The advent of redundant fail-operational digital flight control systems implies that full authority control augmentation designs may be considered; assuming appropriate sensor complements, therefore, systems to the right on the abscissa in Figure 1-1 are at least possibilities during initial design. Examples include the decoupled velocity control system shown on the right of Figure 1-1 and the high gain state-rate feedback procedure used in a recent NASA experiment (Reference 3). Such designs are not applicable, however, to aircraft which rely on less complicated control system implementations. In particular, the AV-8A Harrier and AV-8B Advanced Harrier employ series servos in mechanical flight control links to effect stability and/or control augmentation inputs; flight safety considerations require that the authority of these servos be only a fraction (e.g. 20%) of the total control authority. The limited authority prevents high gain SCAS designs because of saturation. Hence, the basic questions for this type of flight control implementation become: what is the minimum level of SCAS augmentation that is required in conjunction with sophisticated flight displays, and what task limitations result from the limited augmentation level permitted?

This report describes a flight experiment using the U.S. Navy X-22A V/STOL aircraft that addressed these questions specifically for the AV-8B Advanced Harrier. The variable stability/control capability of the X-22A was used to simulate the unaugmented AV-8B characteristics during decelerating approach; data describing the AV-8B were supplied through the



*Numbers are Cooper-Harper pilot ratings, letters are turbulence effect ratings. Two ratings indicates two separate evaluations of a configuration.

Figure 1-1 PILOT RATING DATA FOR PRIMARY MATRIX (NO CROSSWINDS, WITH THRUST VECTOR COMMANDS) FROM REFERENCE 2.

cooperation of the McDonnell-Douglas Aircraft Company. Around this simulation, an electrical analog of the AV-8B control system and series SCAS servos was implemented to investigate a range of possible control system designs. A Smiths' Head-up Display (HUD) unit, as in the AV-8B, was installed in the X-22A and driven by a variable format digital computer to produce a variety of possible display formats and information levels. Combinations of realizable control augmentation concepts and HUD formats were then evaluated for simulated instrument approaches incorporating a deceleration from 65 Kt to hover.

The remainder of this report is organized as follows. Section 2 discusses the genesis of the experiment design in the context of previous research of control display requirements for VTOL instrument approach. Section 3 describes the development of an AV-8B mathematical model and the simulation of this model with the X-22A. Sections 4, 5, and 6 define the experimental parameters investigated for control systems, guidance laws, and display presentations, respectively. The conduct of the experiment is outlined in Section 7, and the results are presented and discussed in Section 8, followed by the conclusions which may be drawn in Section 9. The Appendices contain supportive data documentation.

Section 2
BACKGROUND

2.1 SYNOPSIS OF SECTION

The purposes of this section are to summarize the reasons the experiment described in this report was conducted, to present a brief review of the context within which the experiment was designed, and to define the major goals of the investigation. Because this program was in large part an extension of results obtained in a previous X-22A experiment (Reference 2) to a particular airplane, the review emphasizes the earlier X-22A results, with results from other recent research that provide substantiating information being noted where applicable. The review is used to infer the specific questions that this experiment was designed to investigate.

2.2 PURPOSE OF EXPERIMENT

The general goal of this experiment was to provide flight data relevant to expanding the adverse weather operating capability of VTOL aircraft. Toward this end, the emphasis of the research was on an examination of the effect on pilot rating and performance of the interaction between aircraft dynamic response characteristics, displayed information, and task difficulty during decelerating transitions to hover. In particular, previous results for generic levels of control augmentation and display sophistication were used as a starting point to develop control-display configurations that could be implemented within the constraints of an operational VTOL aircraft. To enhance as much as possible the relevancy of the results, the McDonnell-Douglas AV-8B Advanced Harrier was selected as a representative jet-lift VTOL machine upon which to base the investigation; values of the unaugmented aircraft stability and control derivatives of this aircraft were simulated using the X-22A variable-stability system, the control system implementation of this aircraft was simulated electronically, and the head-up display (HUD) pilot's display unit for the AV-8B was installed in the X-22A. The experiment was therefore designed to investigate combinations of control system/stability augmentation

dynamic characteristics and display presentation formats within the constraints of AV-8B implementation capabilities and operational procedures, with the objective being the definition of satisfactory or acceptable combinations through the use of Cooper-Harper pilot ratings.

2.3 RELATED BACKGROUND

The control-display interaction for VTOL aircraft may be addressed by considering the number of controllers with which the pilot must interact and the general fashion in which he uses these controllers to perform the decelerating approach task. In the general VTOL problem, there are five controllers to be considered: pitch stick, roll stick, rudder pedals, thrust magnitude controller (e.g. throttle), and thrust direction or configuration change controller. Qualitatively, the pilot's control task is (1) to stabilize and control aircraft attitudes (2) to command, in conjunction with thrust magnitude and direction, translational velocities either (3) to follow prescribed velocity profiles and/or (4) to integrate the velocities for comparison with translational position commands. In the context of the closed-loop display-pilot-aircraft system then, each of these control loops must be addressed in the design of displays and control augmentation, and deficiencies in either the control characteristics or displayed information must be accounted for in the design of the other to the extent possible.

The first flight experiment to address the VTOL instrument landing problem specifically with the aim of defining the requirements for, and relationships between, control augmentation and display presentation was the Task III X-22A program documented in Reference 2. This experiment provided the basis and motivation for the program reported herein. Figure 1-1 showed the major results in terms of pilot ratings; a brief description of the control augmentation and display presentation types that were investigated is given in Table 2-1, and the major elements and results of the experiment are given below.

Combinations of the five control systems and five display presentations given in Table 2-1 were evaluated for a task which consisted of

TABLE 2-1a

REFERENCE 2 DISPLAY FORMATS

DISPLAY FORMATS	
• ED-1:	POSITION AND COMMANDED POSITION
• ED-1/FD:	ED-1 WITH SEPARATE THREE-AXIS CONTROL DIRECTOR
• ED-2:	POSITION, COMMANDED POSITION, VELOCITY, AND COMMANDED VELOCITY
• ED-2+:	ED-2 WITH INTEGRATED COLLECTIVE CONTROL DIRECTOR
• ED-3:	POSITION, COMMANDED POSITION, AND VELOCITY WITH INTEGRATED THREE-AXIS CONTROL DIRECTOR

TABLE 2-1b

REFERENCE 2 CONTROL SYSTEMS

CONTROL SYSTEMS
• RATE AUGMENTATION - PITCH, ROLL, AND YAW STABILIZATION
• ATTITUDE/RATE AUGMENTATION - PITCH ATTITUDE COMMAND; ROLL RATE COMMAND/ATTITUDE HOLD; DUAL MODE DIRECTIONAL AXIS-TURN COORDINATION AND HEADING HOLD
• ATTITUDE AUGMENTATION - PITCH AND ROLL ATTITUDE COMMAND; DUAL MODE DIRECTIONAL AXIS
• AUTOMATIC λ - ATTITUDE AUGMENTATION WITH AUTOMATIC THRUST VECTORING
• DECOUPLED VELOCITY CONTROL - DECOUPLED AND AUGMENTED CONTROL OF LONGITUDINAL AND VERTICAL VELOCITIES; DUAL MODE DIRECTIONAL AXIS; AUTOMATIC THRUST VECTORING

two fully hooded instrument approaches from 100 Kt to hover; the elements of the approach task are summarized below:

- level flight localizer acquisition (1700 ft AGL, 100 Kt)
- constant speed (100 Kt) glide slope acquisition (7.5 degrees) at approximately 12,000 ft range
- constant deceleration (.05g) on the glide slope, commencing at a range dependent on headwind (zero-wind range approximately 8000 ft)
- flare to level final approach altitude of 100 ft commencing at approximately 1000 ft range, deceleration continuing to hover
- hover at 100 ft above simulated pad, vertical airwork as desired.

It is emphasized that the pilot ratings given in Figure 1-1 are for this task, which included no breakout to visual conditions, for a head-down display presentation, which included no digital information, and for control systems built around the X-22A aerodynamics, which included essentially unlimited control authorities.

Referring to Figure 1-1, a variety of results can be observed. In a general sense, the most apparent result was the demonstration of the hypothesized interaction between control complexity and display sophistication, particularly for a satisfactory rating (PR $\leq$ 3.5): as the level of augmentation and/or automation increased, the required display presentation decreased from full integrated control director information (ED-3) to velocity and velocity command information both horizontally and vertically (ED-2). It was also apparent that, for a combination to receive a satisfactory rating, the display needed to explicitly include velocity status information. This

requirement was primarily hover-oriented, and was a function of the need to know translational drift velocities accurately for precision station-keeping or touchdown; it is worth noting that, although fully-hooded landings were not considered as part of the evaluation task, a few such "blind" landings were actually performed during the course of the experiment. A final general result can be observed by noting that, as long as velocity was explicitly shown, no trend of pilot rating with display sophistication was found for the decoupled velocity control system: if "good" aircraft response characteristics relative to the required task were provided, the details of the displayed information became less important to satisfactory system performance.

Some specific results also strongly influenced the design of the current experiment

- Satisfactory task performance was achieved without pitch and roll control directors, for manual configuration changes, with the Independent Thrust Vector Inclination Command (ITVIC), if an attitude command system in pitch and roll and a dual-mode yaw command system was implemented. No effect of crosswinds on the ratings for this combination was observed.

- Pilot comments for all the control systems investigated expressed a preference for a control-force-aircraft-attitude relationship in both pitch and roll for instrument hover. This conclusion might be qualified by the fact that the attitude presentation on the electronic display apparently was difficult to interpret intuitively; nonetheless, the comments indicated a desire to obtain the attitude information through control forces rather than visual scanning.

- For VTOL aircraft like the X-22A with low natural height damping in and near the hover, a thrust magnitude director was required for satisfactory task performance if the pilot

was required to perform continuous configuration changes. Relieving the pilot of the configuration change task allowed increased attention to the vertical tracking task and removed the requirement for a control director in that axis.

- Rate augmentation alone was unacceptable for the task investigated unless full control director information was provided. Although performance with the rate system became unacceptable in crosswinds even with full director information, it was considered possible that an improved attitude presentation and the addition of wind direction information would provide an acceptable, although still unsatisfactory, system.

Starting from this basis, questions related to a particular aircraft implementation can be defined. Consider initially the control augmentation aspect of the problem. If one includes instrument hover in the pilot's task, the X-22A results discussed above indicate that a satisfactory control-display combination should include attitude command augmentation at least in one axis. Studies performed for NASA on terminal area operations of lift/cruise fan VTOL designs (e.g. References 4, 5, 6) used attitude command augmentation in pitch and roll plus some directional assistance as baseline control systems for both VMC and IMC situations; similar augmentation was used in X-14 VMC hover tests (Reference 7), and in the NASA VALT helicopter program (Reference 8). An important question, however, is what level of attitude response dynamics is required. References 2 and 8 used augmentation high enough to provide a natural frequency of 1.5 to 2.0 rad/sec, and the levels used in References 4-6 were generally similar; as was discussed in Reference 2, this level of augmentation is consistent with the control response specifications given in MIL-F-83300 (Reference 9). In Reference 7, however, ground simulator results in conjunction with X-14 flight tests indicate that, for <u>hover</u> in visual conditions, levels down to 1.0 rad/sec can provide a satisfactory system.

Ascertaining the minimum level required becomes very important if limited SCAS authorities are a consideration: the difference between

augmenting to 1.0 and 2.0 rad/sec in pitch or roll is a factor of four in attitude feedback. The question which must be answered for an AV-8B implementation is whether the lower levels of augmentation become feasible for an entire transition with the limited actuator authority, and yet still provide satisfactory control characteristics through the deceleration to hover. On this basis, it was decided that one experimental variable would be an attitude command control system with varying levels of feedback operating through a simulation of limited authority series actuators representative of the AV-8B control system. As is described in Section IV of this report, attitude feedbacks to provide frequencies of 1.0, 1.5, and 2.0 rad/sec were selected to address this question.

In the event that attitude command augmentation at a satisfactory level is not feasible, another question is whether the control-display tradeoff can provide a satisfactory system through increased display sophistication in combination with rate damper or rate-command-attitude-hold control systems. These types of control systems are candidates because inputs to the augmentation actuator may not require as much authority as attitude command augmentation does. For example, a McDonnell-Douglas study (Reference 10) aimed at examining ways to improve the AV-8A all-weather landing capability investigated a rate-command-attitude-hold system which was implemented such that the attitude feedbacks were operative only when no pilot force input existed. With this approach, attitude-hold dynamics of approximately 1.5 rad/sec in hover could be achieved, thereby stabilizing the low-frequency unstable unaugmented dynamics, and yet the switching out of the attitude feedbacks during maneuvering reduces the possibility of actuator saturation. A stability augmentation and attitude hold system (SAAHS) of this type will be implemented in the AV-8B.

In the previous X-22A experiment (Reference 2), rate augmentation in combination with three-axis control director information was found to provide an acceptable (6.5 > PR > 3.5) combination if the control director logic was carefully developed and wind/turbulence levels were low; crosswinds,for example, dgraded the system to unacceptable (PR > 6.5). Even though rate and rate-command-attitude-hold control-display combinations can be sensitive to external inputs and desired task performance (pilot technique), it is

important to ascertain for the AV-8B application whether the control deficiencies for these types of augmentation can be compensated for to some extent with additional display sophistication, since the limited actuator authorities may necessitate these augmentation types. In particular, it was decided on this basis to include as variables the proposed basic AV-8B stability augmentation system (SAS), which is similar to that of the AV-8A and includes only angular rate feedbacks plus a small amount of directional assistance through lateral acceleration, and at least one rate-command-attitude-hold control augmentation system to be implemented in a manner analogous to Reference 10 (see Section IV).

It is important to note that the evaluation task, in terms of the deceleration profile, was more difficult in the previous X-22A experiment than for the AV-8B application. Reference 2 investigation considered a constant deceleration which required a continuous control task on the part of the pilot through the transition; the approach profiles considered in References 3, 5, and 6 similarly required a continuous control task even though the decelerations were different. For the AV-8B, however, a "one-step" thrust direction change (which yields essentially an exponential deceleration) is appropriate (e.g., References 10, 11), because thrust magnitude (power) and direction are commanded by separate left-hand controllers. The one-step deceleration initiation means that the thrust direction control through the deceleration is open-loop, which means a reduced pilot workload in this axis and possibly less stringent control-display requirements than in Reference 2. As far as the dynamic response characteristics are concerned, of course, the simpler task does not by itself imply that rate-damping-only, for example, will be satisfactory, because the basic aircraft characteristics still predominate. An example is a follow-on VALT helicopter experiment (Reference 12), in which rate-damping-only was found unacceptable, even with control director displays, for a realtively simple constant attitude deceleration task; in this case, the highly unstable positive real root of the CH-47 test vehicle was the cause. In an extensive series of ground simulator runs prior to this flight experiment, using a simulation of the AV-8A documented in Reference 13, it was found that rate-damping-only control systems for the AV-8A

could in fact be flown through the deceleration even without control directors, and therefore the basic AV-8B SAS was considered to be a viable candidate for the flight experiment even though previous results seemed contradicted.

Consider now the display aspect of the problem. Assuming again the inclusion of instrument hover in the pilot's task, the previous X-22A experiment results indicate that the displayed information must include translational velocity information explicitly. A plan view velocity vector was also used in the CL-84 HUD flight experiment (Reference 14) and the NASA lift/cruise fan VTOL ground simulator experiment (Reference 3). The proposed AV-8B HUD format includes digital airspeed readout, but does not include analog representations of either the velocity vector the pilot must control or of plan-view position information (Reference 10). The question that must be answered in whether the simpler task of the current program renders the analog representation of velocity and commanded velocity examined in Reference 2 unnecessary; in the AV-8A, angle of attack is the primary controlled variable through the open-loop deceleration, and the proposed format includes this information. The proposed format also considers a two-axis control director (roll, thrust magnitude), whereas previous work has generally considered three-axis control director information (pitch, roll, thrust magnitude - e.g., References 2, 3, 8, 12); since pitch and roll control directors were not found to be necessary with attitude command augmentation in the previous X-22A experiment, the presence or absence of such directors plus the number of axes considered was selected as an experimental variable.

A basic question relative to HUD formats is the scaling of the pitch attitude display. One-to-one scaling with the real world may be too sensitive for terminal area operations, given the limited vertical field of view of current equipment, if the airplane exhibits poor longitudinal control characteristics. The proposed AV-8B format uses 3:1 scaling (Reference 10), although scalings of 5:1 have also been suggested, and presents pitch attitude via a "ladder" format in which the rungs are open in the center. A typical head-down attitude indicator, however, would scale to approximately 16:1 if shown head up, and the scaling used in the previous X-22A experiment

for the head-down electronic formats were consistent with this value. To ascertain the influence of the attitude scaling, formats with consistent information content but attitude presentations taken from either the Reference 10 format or the Reference 2 formats were designed as an experimental variable.

A final display question of interest is the effect of permitting a breakout to visual conditions for the hover portion of the task on the display information requirements. Although the previous X-22A experiment indicated the need for explicit display of translational velocities, it was clear that the hover portion of the task had a major influence on this requirement. To examine this influence, the evaluation procedure included pilot ratings excluding the hover (see Section VII), and selected configurations were evaluated for both a deceleration to hover entirely on instruments and with a breakout for hover.

2.4 EXPERIMENT GOALS

Based on the considerations outlined in the previous subsections, the specific goals toward which this experiment was oriented were:

- Develop a simulation, using the X-22A variable stability variable display aircraft, of the AV-8B jet-lift VTOL for terminal area operations.

- Investigate control-display requirements for VTOL instrument terminal area operations given constraints on allowable augmentation authority and predicated upon AV-8B aerodynamic characteristics. Use proposed AV-8B control system and display presentation as baseline.

- Emphasize display information variations for head-up presentation to improve system performance for less desirable control system implementations.

- Examine influence of increasing augmentation authorities.

- Examine influence of permitting breakout to visual conditions.

Section 3
AV-8B MODEL AND SIMULATION

3.1 SYNOPSIS OF SECTION

The purpose of this section is to present the mathematical model used to represent the McDonnell-Douglas AV-8B Advanced Harrier, describe the methods used to simulate this model with the X-22A, and discuss the validity of the resulting simulation. Accordingly, the first subsection summarizes the development of a linear model from MCAIR-supplied data and documents the stability/control derivatives that comprise the selected model. In the next subsection, the methods used to simulate this linear model with a linear representation of the X-22A are outlined. The resulting idealized simulation is compared with the AV-8B model in the next subsection in terms of time history matches. Finally, a summary of the pilot acceptance flights for simulation verification is given.

3.2 DEVELOPMENT OF AV-8B MATHEMATICAL MODEL

The variable stability system of the X-22A is of the response feedback type. As implemented in the X-22A, the characteristics of such a system imply certain constraints on the model of the aircraft to be simulated. In particular, the system commands designated control motions linearly proportional to measured signals less "reference" values (which may be constant or a function of flight condition) to alter the basic stability/control derivatives of the X-22A directly; the proportionality between a measurement and a control motion may be varied as a function of flight condition but it is linear (e.g., the control cannot move as the square of the measurement). As a result, the model of the AV-8B must be developed in terms of reference conditions which explicitly depend on a defined evaluation task, and "linearized" (though non-constant) stability and control derivatives around these references.

As an example, consider the longitudinal equations of motion which, with some simplifications, may be written:

$$\dot{u} + g \sin\theta + \dot{\theta} w = X(u, w, q, \delta_T, \delta_E, \theta_j)$$

$$\dot{w} - g \cos\theta - \dot{\theta} u = Z(u, w, q, \delta_T, \delta_E, \theta_j)$$

$$\ddot{\theta} = M(u, w, q, \delta_T, \delta_E, \theta_j)$$

$$\gamma = \theta - \alpha$$

$$\alpha = \tan^{-1}(w/u)$$

By requiring that $\ddot{\theta} = \dot{\theta} = q = \dot{\gamma} = \dot{\alpha} = 0$ be included as reference conditions, this set of equations may be reduced to three equations in seven unknowns: $\dot{u}$, γ, u, w, δ_T, δ_E, $\dot{\theta}_j$. By specifying four of the unknowns through a selection of the evaluation task, the remaining three may be uniquely determined. For example, the reference conditions at various points along the AV-8B reference trajectory may be computed by specifying γ, α, u and θ_j and calculating the required values of $\dot{u}$, δ_T, and δ_E from the complete "global" representation of the aerodynamic/propulsive forces and moments acting on the aircraft. If the deceleration schedule is defined for the task, then $\dot{u}$, γ, u and θ_j (or w) may be specified and the reference values of δ_T, δ_E and w (or θ_j) may be calculated. These reference conditions, either specified or calculated, are denoted by the subscript R for convenience.

The coefficients for a Taylor series representation of the aerodynamic/propulsive forces and moments may now be obtained in a manner similar to the technique described in Reference 15. The general approach used to calculate the longitudinal dimensional derivatives is to:

- calculate the values of X, Z, and M which correspond to the reference conditions u_R, w_R, q_R, δ_{T_R}, δ_{E_R}, θ_{j_R} at selected points on the reference trajectory

- perturb one of the variables in suitable increments from the reference value and determine the corresponding values of X, Z and M.

- calculate and plot the change in X, Z and M versus the change in the variable being perturbed

- fit an n^{th} order polynomial to the data on a least-square error basis (e.g. n = 3)

- differentiate the polynomial successively to determine first, second, and third-order derivatives.

The cross derivatives such as $X_{u\delta_T}$ may be obtained by repeating the above procedure for a series of throttle positions at positive and negative increments from the reference value, cross-plotting the resultant values of X_u vs. δ_T, and calculating the slope of the curve.

The only mathematical model of the AV-8B that exists is a nonlinear table-look-up simulator computer model at MCAIR, since, at the time of the model development, the aircraft had not been built and no flight test data existed. It was therefore necessary to develop an appropriate model from this computer program. At the request of Calspan and NADC, MCAIR defined two reference approach trajectories for the AV-8B, one for a 3^o approach from 105 Kt, and one for a 5^o approach from 65 Kt. For each trajectory, reference conditions for several "trim" velocity-nozzle combinations were defined; these conditions are summarized in Table 3-1. A computer program was then written to interact with the simulator computer model: for each reference condition, changes in aerodynamic and thrust forces and moments were computed for a range of perturbations in one variable at a time as discussed above (e.g. u, v, w, etc.). The forces and moments were then plotted versus the

TABLE 3-1a 105 KT PROFILE REFERENCE TRAJECTORY

REFERENCE CONDITIONS

GW = 16300 LBS
CG = 0.0569 $\bar{C}$
(4) PYLONS, GUNS & AMMO
δ_F = 25°

CONDITION	V (KTS)	α (DEG)	θ (DEG)	γ (DEG)	θ_J (DEG)	RPM (%)	δ_T (%)	δ_H (DEG)	$\delta_{ST_{LONG}}$ (%)	x_B (FT/SEC^2)	z_B (FT/SEC^2)
A	105	8.0	8.0	0	62.7	84.4	44.4	1.20	46.4	0.004	-0.030
B	105	8.0	5.0	-3	67.0	84.4	44.4	1.23	46.2	0.002	-0.031
C	105	8.0	5.0	-3	81.0	85.9	45.4	1.27	46.0	-5.678	-0.829
D	95	8.0	5.0	-3	81.0	88.9	51.2	1.18	46.5	-4.940	-0.725
E	75	8.0	5.0	-3	81.0	93.1	66.2	0.97	47.5	-3.336	-0.500
F	55	8.0	5.0	-3	81.0	95.6	75.7	0.77	48.6	-1.734	-0.275
G	35	8.0	5.0	-3	81.0	96.9	80.4	0.57	49.6	-0.373	-0.083
H	35	8.0	8.0	0	81.0	97.0	80.6	0.57	49.6	-2.041	-0.318
I	35	4.5	4.5	0	81.0	97.5	82.5	0.42	50.3	0.002	-0.030
J	0	-	8.0	0	81.0	97.6	82.6	0.30	51.0	-0.309	-0.074
K	0	-	7.4	0	81.0	97.6	82.6	0.30	51.0	0.003	-0.030

TABLE 3-1b 65 KT PROFILE REFERENCE TRAJECTORY

REFERENCE CONDITIONS

GW = 16300 LBS
CG = 0.0569 $\bar{C}$
(4) PYLONS, GUNS & AMMO
δ_F = 60°

CONDITION	V (KTS)	α (DEG)	θ (DEG)	γ (DEG)	θ_J (DEG)	RPM (%)	δ_T (%)	δ_H (DEG)	$\delta_{ST_{LONG}}$ (%)	x_B (FT/SEC^2)	z_B (FT/SEC^2)
L	65	8.0	8.0	0	69.9	91.3	59.5	0.40	50.5	0.009	-0.031
M	65	8.0	3.0	-5	75.9	91.3	59.5	0.35	50.7	0.002	-0.030
N	65	8.0	3.0	-5	81.0	91.7	61.0	0.28	51.0	-2.371	-0.364
Ø	50	8.0	3.0	-5	81.0	94.3	70.9	0.39	50.5	-0.837	-0.148
P	35	8.0	3.0	-5	81.0	96.0	77.4	0.41	50.4	0.447	0.032
Q	35	8.0	8.0	0	81.0	96.2	77.9	0.40	50.5	-2.332	-0.359
R	35	3.8	3.8	0	81.0	96.7	79.7	0.20	51.5	0.002	-0.030
S	0	-	8.0	0	81.0	97.6	82.6	0.30	51.0	-0.309	-0.074
T	0	-	7.4	0	81.0	97.6	82.6	0.30	51.0	0.003	-0.030

perturbation in order to determine appropriate linearized stability and control derivatives; an example is given in Figure 3-1.

Table 3-2 summarizes the longitudinal and lateral-directional derivatives determined from the force-moment plots for the twenty reference conditions. These values were used to define a "single-model" representation at six (6) velocities that would be approximately correct for both reference trajectories; these derivatives are summarized in Table 3-3.

Time histories from this model were compared to those of the MCAIR simulator program for trim level flight conditions at 0, 65, and 105 Kt. Since the computer outputs are different scales, it is not possible to show this comparison here directly. In general, it was judged that the linear model represented the nonlinear time histories reasonably well at these flight conditions. The model given in Table 3-3 was therefore used as the basis for the computation of the simulation gains.

3.3 SIMULATION METHODOLOGY

3.3.1 Lateral-Directional

The lateral-directional rigid-body equations of motion of the AV-8B may be described by a three degree-of-freedom, fourth-order system:

$$\dot{x} = Fx + Gu$$

x = state vector of aircraft (4 elements)
F = aircraft system matrix (3 x 4)
G = aircraft control matrix (3 x 2)
u = aircraft control vector (2 elements - roll and yaw control)

Thus, twelve state coefficients and six control coefficients are, in general, required to describe fully the lateral-directional dynamics of the aircraft.

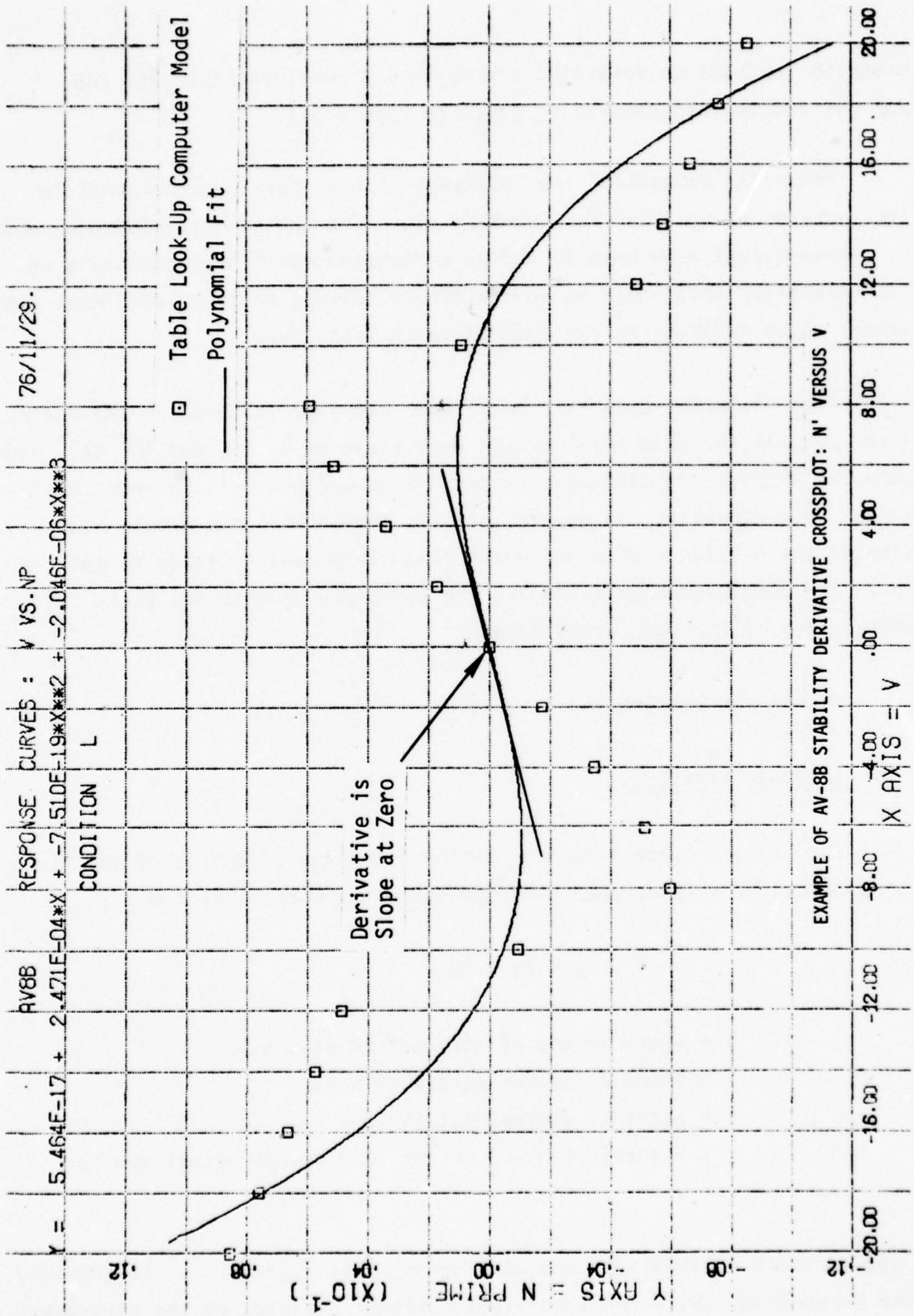


Figure 3-1 EXAMPLE OF AV-8B STABILITY DERIVATIVE CROSSPLOT: N' VERSUS V

TABLE 3-2a AV-8B VELOCITY DERIVATIVES

COND.	X_u	Z_u	M_u		Y_v	L'_v	N'_v		X_w	Z_w	M_w	
A	-.039	-.109	-.00042*		-.138	-.0128	.00467		.0425	-.375	-.0067	
B	-.040	-.104	-.00025*		-.138	-.0130	.00467		.040	-.389	-.0070	
C	-.043	-.088	+.00026*		-.139	-.0135	.0042		.029	-.435	-.0074	
D	-.043	-.075	-.00005*		-.130	-.0140	.0030		.020*	-.405	-.0050	
E	-.044	-.046	-.00044		-.111	-.0155*	.0005*		.0087*	-.335	-.00076*	
F	-.040	-.019	-.00023		-.091	-.0133	-.00065*		.00235*	-.228	+.0023	
G	-.035	-.0038*	+.00003		-.069	-.0117*	-.0021		.0038*	-.192	+.0039	
H	-.035	-.0038*	+.00003		-.069	-.0113*	-.0022		0.0*	-.175	No Data	
I	-.036	+.00075*	+.00015*		-.070	-.0115*	-.0021		-.0071*	-.181	+.0040	
J	-.025*	0.0*	0.0		-.034	0.0**	-.0034		0.0*	-.0175	.0042	
K	-.025*	0.0*	0.0		-.034	0.0**	-.0034		0.0*	-.0175	.0042	
L	-.055	-.102	-.0028		-.106	-.020*	+.0060*		.036*	-.233	+.0024	
M	-.057	-.092	-.0027		-.106	-.024*	+.0056*		.035*	-.230	+.0022**	
N	-.059	-.084	-.0026		-.106	-.021*	+.0066		.031*	-.228	+.0020	
O	-.048	-.054	-.0020		-.089	-.024*	-.0011		0.0*	-.188	+.0040	
P	-.043	-.032	-.0013		-.071	-.020*	-.0019		-.0094	-.15	+.0050	
Q	-.041	-.032	-.0013		-.071	-.020*	-.0021		0.0	-.14	+.0047	
R	-.044	-.027	-.0013		-.073	-.016*	-.0018		.011	-.16	+.0049	
S	-.025*	0.0*	0.0		-.034	-.002	-.0034		0.0	-.018	+.0042	
T	-.025*	0.0*	0.0		-.034	-.002	-.0034		0.0	-.018	+.0042	
	*Used +u perterba- tions	*2-sided Est.Avg.	*Est.Avg			*Weighted toward large v **Very non-linear	*Very non- linear		*Est.		*Nonlinear **Avg.	

TABLE 3-2b AV-8B ROTARY DERIVATIVES

COND.		X_q	Z_q	M_q		Y_p	L'_p	N'_p		Y_r	L'_r	N'_r
A		.11	-.79	-.28	1	0	-1.37	-.125		-.210	.492	-.203
B		.11	-.79	-.28		0	-1.37	-.125		-.210	.492	-.203
C		.11	-.79	-.28		0	-1.37	-.125		-.215	.492	-.204
D		.10	-.72	-.259		0	-1.24	-.113		-.225	.448	-.189
E		.079	-.56	-.214		0	-.981	-.089		-.235	.358	-.158
F		.054	-.42	-.170		0	-.728	-.064		-.235	.261	-.127
G		.025	-.28	-.129		0	-.511	-.039		-.235	.154	-.098
H		.037	-.28	-.129		0	-.507	-.044		-.235	.177	-.096
I		.021	-.28	-.129		0	-.518	-.032		-.237	.126	-.101
J		0	-.05	-.056		0	-.120	-.0047		-.223	.017	-.042
K		0	-.05	-.056		0	-.120	-.0047		-.223	.017	-.042
L		.069	-.49	-.19		0	-.748	-.0703		-.230	.312	-.141
M		.069	-.49	-.19		0	-.748	-.0703		-.230	.312	-.141
N		.069	-.49	-.19		0	-.748	-.0703		-.231	.312	-.141
O		.042	-.38	-.158		0	-.594	-.0514		-.235	.226	-.120
P		.017	-.28	-.128		0	-.456	-.0338		-.233	.139	-.100
Q		.037	-.28	-.127		0	-.449	-.0397		-.229	.176	-.095
R		.018	-.28	-.128		0	-.463	-.0269		-.235	.117	-.101
S		0	-.05	-.056		0	-.137	-.0057		-.223	.017	-.0418
T		0	-.05	-.056		0	-.137	-.0057		-.223	.017	-.0418

TABLE 3-2c AV-8B LONGITUDINAL CONTROL DERIVATIVES

COND		X_{θ_j}	Z_{θ_j}	M_{θ_j}		X_{δ_T}	Z_{δ_T}	M_{δ_T}		$X_{\delta_{ES}}$	$Z_{\delta_{ES}}$	$M_{\delta_{ES}}$
A		-.385	-.055	.0012		.60	-1.41	-.0076		-.176	-.176	.241
B		-.395	-.031	.0011		.48	-1.44	-.009		-.176	-.229	.243
C		-.422	-.042	.0005		.066	-1.75	-.013		-.116	-.229	.250
D		-.463	-.045	-.00051		.13	-2.25	-.030		-.120	-.281	.250
E		-.516	-.027	-.00127		.20	-2.20	-.039		-.128	-.352	.250
F		-.543	-.052	-.00155		.25	-2.33	-.039		-.135	-.352	.246
G		-.554	-.064	-.00168		.29	-2.49	-.040		-.149	-.352	.239
H		-.555	-.064	-.00168		.29	-2.50	-.040		-.158	-.352	.239
I		-.561	-.073	-.00168		.29	-2.55	-.0398		-.158	-.352	.241
J		-.555	-.066	-.00167		.34	-2.55	-.0362		-.163	-.352	.230
K		-.555	-.066	-.00167		.34	-2.55	-.0362		-.163	-.352	.230
L		-.456	-.067	-.0011		.66	-2.11	-.031		-.179	-.293	.220
M		-.468	-.017	-.0009		.42	-2.18	-.033		-.148	-.270	.220
N		-.480	-.017	-.0011		.22	-2.21	-.033		-.130	-.289	.221
O		-.514	-.039	-.0014		.23	-2.24	-.034		-.134	-.289	.229
P		-.538	-.055	-.0016		.28	-2.38	-.036		-.183	-.192	.232
Q		-.516	-.052	-.0014		.26	-2.24	-.034		-.133	-.396	.233
R		-.548	-.058	-.0015		.28	-2.45	-.035		-.144	-.322	.232
S		-.555	-.066	-.0017		.34	-2.55	-.036		-.144	-.350	.231
T		-.555	-.066	-.0017		.34	-2.55	-.036		-.144	-.350	.231

TABLE 3-2d AV-8B LATERAL-DIRECTIONAL CONTROL DERIVATIVES

COND		$Y_{\delta_{AS}}$	$L'_{\delta_{AS}}$	$N'_{\delta_{AS}}$		$Y_{\delta_{RP}}$	$L'_{\delta_{RP}}$	$N'_{\delta_{RP}}$	
A		-.084	.625	.053		-.891	-.127	.262	
B		-.084	.625	.053		-.891	-.127	.262	
C		-.084	.638	.053		-.912	-.127	.269	
D		-.070	.638	.048		-.855	-.113	.262	
E		-.043	.598	.044		-.785	-.092	.255	
F		-.023	.585	.039		-.735	-.078	.240	
G		-.009	.541	.035		-.707	-.066	.233	
H		-.009	.541	.035		-.707	-.068	.233	
I		-.008	.546	.036		-.707	-.069	.233	
J		0	.515	.032		-.686	-.059	.226	
K		0	.515	.032		-.686	-.059	.226	
L		~0	.51	.034		-.703	-.0818	.230	
M		~0	.51	.034		-.702	-.0817	.230	
N		~0	.51	.034		-.707	-.083	.231	
O		~0	.542	.0354		-.696	-.070	.231	
P		~0	.552	.0354		-.690	-.063	.229	
Q		~0	.504	.0347		-.669	-.064	.221	
R		~0	.567	.0354		-.692	-.067	.228	
S		~0	.567	.0354		-.687	-.059	.225	
T		~0	.567	.0354		-.687	-.059	.225	

TABLE 3-3a "SINGLE-MODEL" AV-8B LONGITUDINAL MODEL

	V_o(Kt)	0	30	50	65	80	105
	X_u	-.044	-.044	-.044	-.044	-.044	-.044
	Z_u	0.0	-.023	-.054	-.092	-.101	-.105
	M_u	0.0	-.0009	-.0020	-.0026	-.0008	0.0
	X_w	0.0	0.0	+.0035	+.010	+.0175	+.035
	Z_w	-.018	-.125	-.195	-.240	-.300	-.390
	M_w	+.0042	+.0047	+.0040	+.0021	-.0015	-.0070
	X_q	0	+.03	+.05	+.052	+.085	.11
	Z_q	-.05	-.29	-.40	-.47	-.61	-.79
	M_q	-.056	-.118	-.160	-.191	-.224	-.280
	$X_{\delta_{ES}}$	-.161	-.151	-.145	-.139	-.134	-.126
	$Z_{\delta_{ES}}$	-.350	-.340	-.335	-.330	-.295	-.205
	$M_{\delta_{ES}}$	.230	.235	.237	.240	.241	.243
$\theta_j =$ 81	X_{δ_T}	.34	.30	.262	.225	.180	.140
	Z_{δ_T}	-2.55	-2.46	-2.37	-2.26	-2.10	-1.75
	M_{δ_T}	-0.036	-0.036	-0.036	-0.036	-0.036	-0.036
Trim	X_{δ_T}				.66		.60
	Z_{δ_T}				-2.11		-1.41
$\theta_j =$ 81°	X_{θ_j}	-.555	-.546	-.530	-.510	-.476	-.400
	Z_{θ_j}	-.066	-.061	-.050	-.028	-.023	-.040
	M_{θ_j}	0	0	0	0	0	0
Trim	X_{θ_j}				-.456		-.380
	Z_{θ_j}				-.066		-.055

TABLE 3-3b "SINGLE-MODEL" AV-8B LATERAL-DIRECTIONAL MODEL

V_o		0	30	50	65	80	105
Y_v		-.034	-.063	-.088	-.104	-.120	-.138
L'_v		-.0020	-.0144	-.0197	-.0204	-.0184	-.0104
N'_v		-.0036	-.0021	-.0010	0.0	+.0014	.0047
Y_p		0	0	0	0	0	0
L'_p		-.13	-.42	-.62	-.79	-1.0	-1.38
N'_p		-.005	-.032	-.053	-.072	-.091	-.126
Y_r		-.225	-.24	-.24	-.235	-.235	-.215
L'_r		.015	.15	.24	.31	.375	.49
N'_r		-.042	-.088	-.12	-.142	-.164	-.203
$Y_{\delta_{as}}$		0	-.006	-.015	-.026	-.039	-.065
$L'_{\delta_{as}}$		0.5	0.5	0.5	0.5	0.5	0.5
$N'_{\delta_{as}}$		.030	.030	.031	.033	.035	.040
$Y_{\delta_{RP}}$		-.68	-.67	-.70	-.75	-.80	-.90
$L'_{\delta_{RP}}$		-.060	-.065	-.075	-.080	-.095	-.13
$N'_{\delta_{RP}}$		.225	.235	.243	.248	.255	.265

With two independent lateral-directional controls, roll and yaw, available in the X-22A, only two of the three degrees of freedom may be independently controlled. Thus, eight state coefficients - controllable degrees of freedom (2) times order of system (4) - and four control coefficients - controllable degrees of freedom (2) times number of controls (2) - may be specified. Therefore, the X-22A using only roll and yaw controls, is capable of reproducing twelve of the eighteen parameters which describe the lateral-directional dynamics of the basic AV-8B; the six independent coefficients which cannot be directly controlled are the side force derivatives, of which the side-force-due-to-sideslip (Y_β) has the dominant effect on the AV-8B's lateral-directional flying qualities. Accordingly, the process whose end product is an acceptable in-flight simulation of the basic AV-8B's lateral-directional characteristics initially involves the selection of the twelve flying qualities parameters to be specified for the simulation.

It was found that the best time history matches were obtained for the 0, 30, 50, and 65 Kt onditions by matching all of the roll and yaw derivatives; although Y_v of X-22A is approximately twice that of the AV-8B, at the lower speeds the primary effect of this mismatch is different lateral acceleration responses. For the 80 and 105 Kt flight conditions, a Calspan-developed computerized gain computation procedure which specifies modal parameters was used instead of derivative matching (Reference 16). The input requirements for this program include: 1) the X-22A dimensional stability/control derivatives in primed form, airspeed, and angle of attack at the flight conditions of interest and 2) twelve specified AV-8B stability/control parameters at each flight condition expressed in terms of modal characteristics and stability/control derivatives. Included in the program output for each flight condition are:

- the VSS gains required to achieve the specified parameters
- the stability/control derivatives of the simulated aircraft, i.e., X-22A with VSS in operation with calculated gains
- equations of motion and modal characteristics of simulated aircraft

- roots and transfer functions of simulated aircraft
- time histories of simulated aircraft response to control inputs

The simulation methodology, dictated in part by the structure of the computer program, was to specify the values of the following parameters at each flight condition:

ζ_d	$\lvert\phi/\beta\rvert_d$	$L'_{\delta_{as}}$
ω_d	$L'_\beta\ (=0)$	$N'_{\delta_{as}}$
τ_R	$N'_\beta\ (=0)$	$L'_{\delta_{rp}}$
τ_S		$N'_{\delta_{rp}}$

The remaining parameter to be specified, $\measuredangle(\phi/\beta)_d$, was iterated about its nominal value in an effort to achieve the best match of the derivatives L'_β and N'_β and the flying qualities parameter ω_ϕ/ω_d.

3.3.2 Longitudinal

The longitudinal simulation problem is similar to but more difficult than the lateral/directional situation. Again, three degree-of-freedom motion is to be simulated with two controllers, if possible; although the use of the elevons in a collective fashion would provide three controllers and hence exact simulation could be possible, the elevons would have limited authority and hence it was judged desirable to avoid using feedbacks to them. Unfortunately, the digital computer design procedure used to compute the lateral/directional feedback gains was not an appropriate tool for the longitudinal design problem because:

- The collective blade controller changes from being effective at changing vertical-force equation characteristics at low speeds to changing longitudinal-force equation characteristics at high speeds. Hence a uniform set of desirable modal characteristics cannot be simulated over the entire velocity range.

- Although the majority of important modal characteristics for lateral/directional flying qualities can be achieved through control of the yaw and roll moment equations, for the longitudinal problem the individual force equations (particularly longitudinal force) are not as effective. In addition, equivalent modal characteristics (e.g. $|\phi/\beta|_d$) are not as well defined in terms of flying qualities for the longitudinal problem, particularly in transition.

The longitudinal simulation gains were therefore found using procedures developed in Reference 13: the control gearings were set to reproduce the AV-8B control derivatives, and included the use of collective elevons, and the feedback gains were found via a modification to implicit model-following optimal control theory. This latter procedure is summarized below.

A problem with the optimal control procedure, which is admittedly peculiar to the application of simulating one aircraft with another, is that the closed-loop system is guaranteed to be stable and will be so <u>even if the model has unstable eigenvalues</u>. For the AV-8B application, each flight condition has at least one unstable root. Hence, a modification to the theory was developed on the basis of the root-square-locus (Reference 17) situation for this problem.

Figure 3-2 sketches the root-square-loci for two examples where the plant and model are both second order and can be "matched" exactly (e.g. one row different, one controller): in (a), the model has stable eigenvalues, and in (b) the model has unstable eigenvalues with the same frequency but opposite damping. The adjoint poles and zeros are shown as dashed symbols. As can be seen from these sketches, what happens when the model is unstable is that the plant roots migrate to the <u>adjoint</u> zeros (which are stable) to ensure a stable augmented system; in fact, for this example the optimal gains would be computed to be the same for both (a) and (b). The optimal control procedure will always use the poles and zeros on the left-hand side in computing the gains, and will never try to "follow" an unstable model if Q and R meet positive-definite requirements.

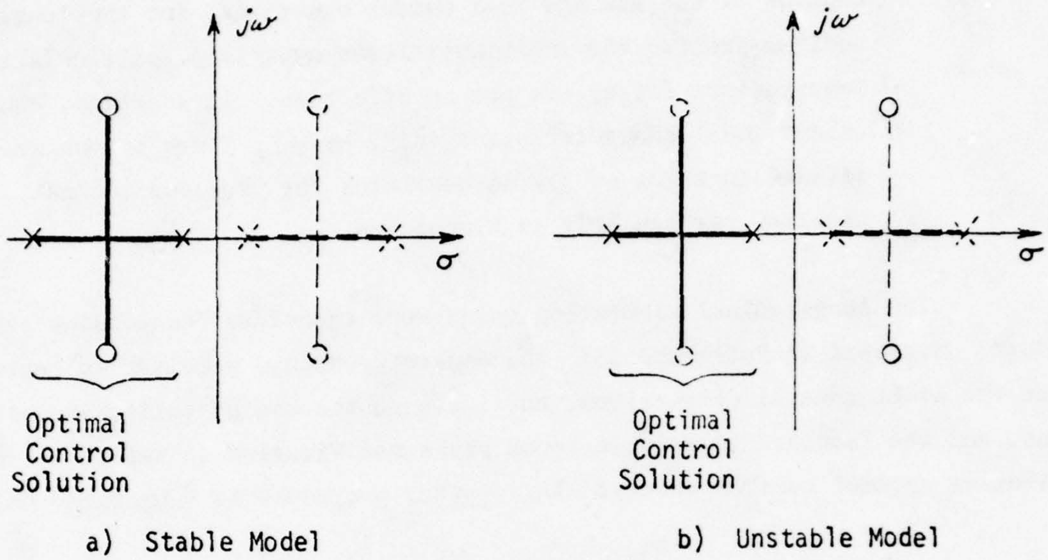


Figure 3-2 OPTIMAL CONTROL EXAMPLES IN S-PLANE

One way to circumvent the problem is to relax the requirement on Q and R, but an easier and preferable procedure is suggested by the root-square-loci. If the computations could be performed for a transformed system in which the model and plant are both stable, then all the adjoint roots would again be in the right-half plane, and the plant roots would migrate to the actual model roots instead of their adjoints. A procedure to accomplish this transformed computation is given below.

The eigenvalues of the plant and model can be expressed by:

$$P^{-1} F P = \Lambda_p , \quad M^{-1} L M = \Lambda_m$$

Choose a positive number "n" such that, when it is subtracted from the most unstable eigenvalue, real or complex, the new eigenvalue is stable. Then define:

$$\hat{\Lambda}_p = \Lambda_p - nI, \quad \hat{\Lambda}_m = \Lambda_m - nI$$

It is then easy to show that:

$$P^{-1}\hat{F}P = \hat{\Lambda}_p \qquad \text{if} \quad \hat{F} = F - nI$$
$$M^{-1}\hat{L}M = \hat{\Lambda}_m \qquad \text{if} \quad \hat{L} = L - nI$$

We now solve the following optimal control problem:

Minimize

$$J = \int_0^{\infty} \left[(\dot{x} - \dot{y})^T Q (\dot{x} - \dot{y}) + u^T R u \right] dt$$

Subject to: $\dot{x} = \hat{F}x + Gu$

$\dot{y} = \hat{L}y$

$x = y$

For this transformed problem, all of the system poles and zeros are on the left-hand side of the S-plane and all the adjoint roots are in the right-hand side; hence, conventional juggling of the Q and R matrices can be used to get the augmented plant roots as close to the model roots as desired.

Calling the resulting optimal control gain matrix $\hat{K}$ and the augmented eigenvalues in the transformed system $\hat{\Lambda}_A$, we may now write:

$$A^{-1}(\hat{F} - G\hat{K})A = \hat{\Lambda}_A$$

Then: $$A^{-1}(F - G\hat{K})A = \hat{\Lambda}_A + nI$$

Hence, using the computed gains with the original, untransformed plant matrix yields a set of eigenvalues $\Lambda_A = \hat{\Lambda}_A + nI$; if the optimal control procedure made $\hat{\Lambda}_A \cong \hat{\Lambda}_m$, then $\Lambda_A \cong \Lambda_m$ as desired because $\Lambda_m = \hat{\Lambda}_m + nI$. Figure 3-3 sketches the result of this procedure for the unstable model example shown in Figure 3-2b.

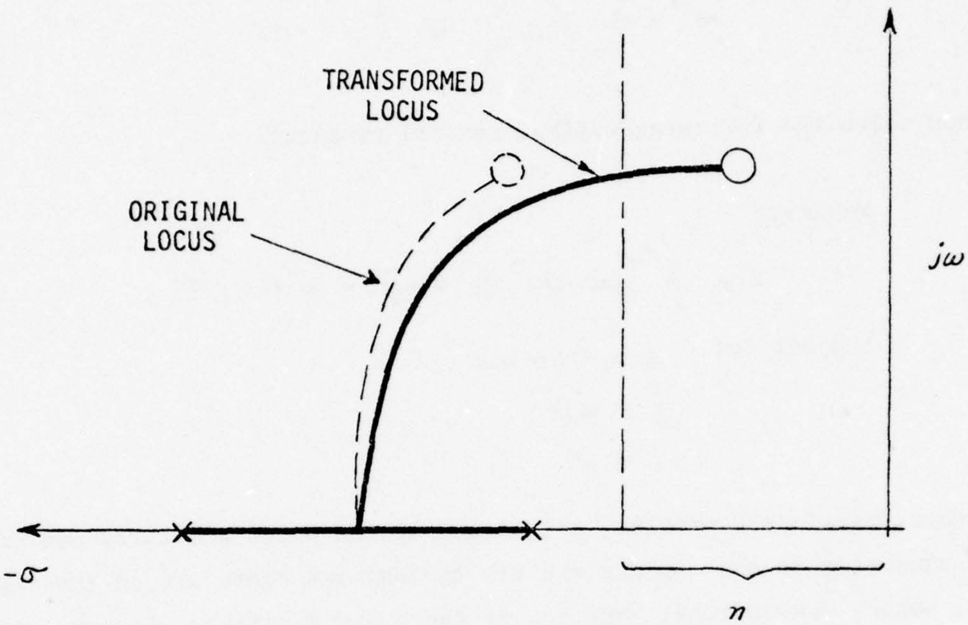


Figure 3-3 EXAMPLE OF TRANSFORMED OPTIMAL CONTROL SOLUTION

In addition to simulating the stability and control characteristics for each operating point, it was necessary to include pitch stick and throttle trim variations of the AV-8B in the simulation, and to devise a duct rotation scheme which approximated the deceleration caused by a nozzle angle change in the AV-8B. Approximate trim changes from Table 3-1 are shown in Figure 3-4; the implementation characteristics are shown in Figure 3-5. The scheme used to simulate the deceleration caused by AV-8B nozzle rotation was based upon the desire to simulate not only the long-term deceleration characteristics of the vehicle, dictated primarily by the AV-8B drag damping, but also the short-term deceleration caused by the almost instantaneous rotation of the thrust vector. Accordingly, the input from the nozzle angle controller was fed both to the automatic duct rotation circuit through a running integrator as a duct angle command and to the

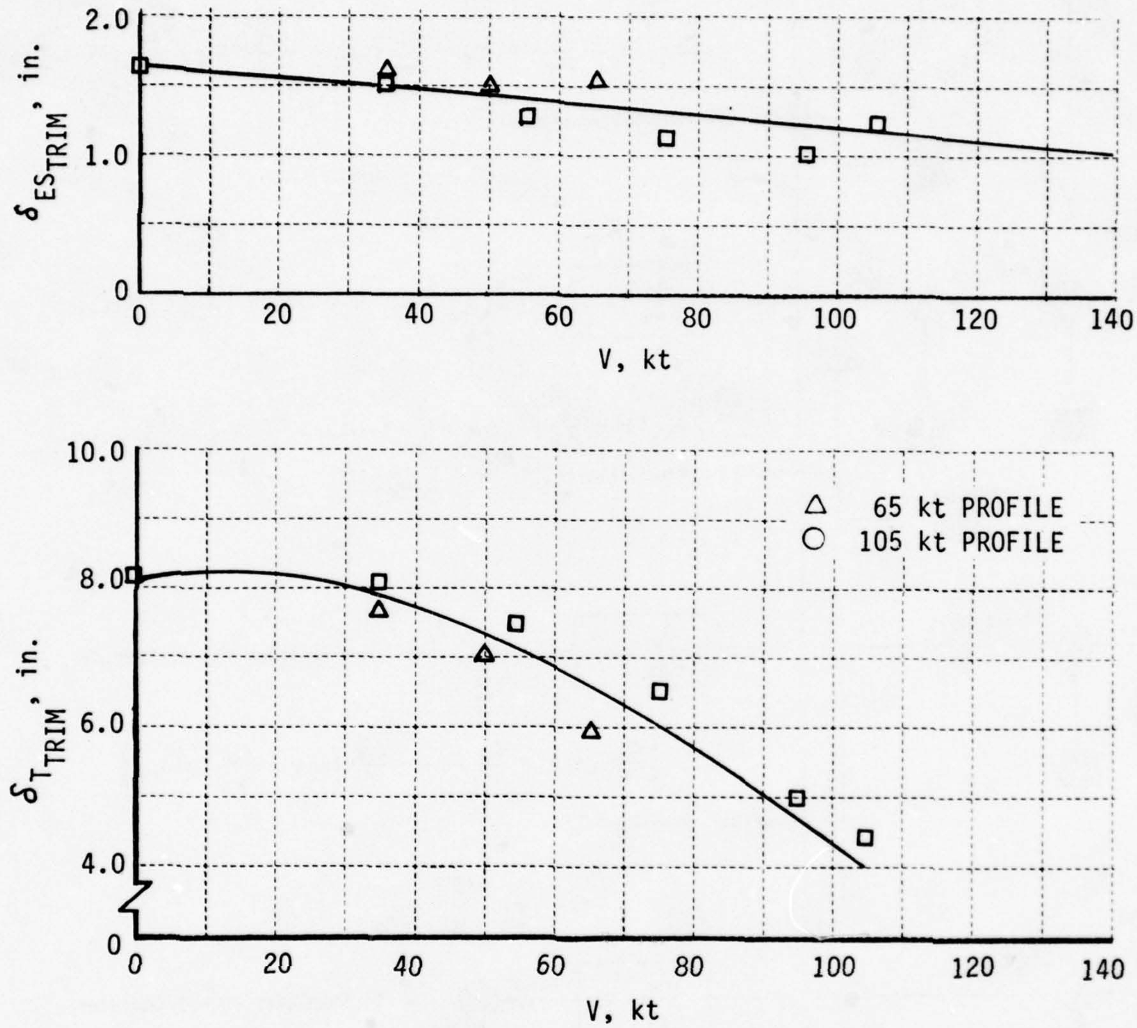


Figure 3-4 AV-8B APPROXIMATE TRIM RELATIONSHIPS

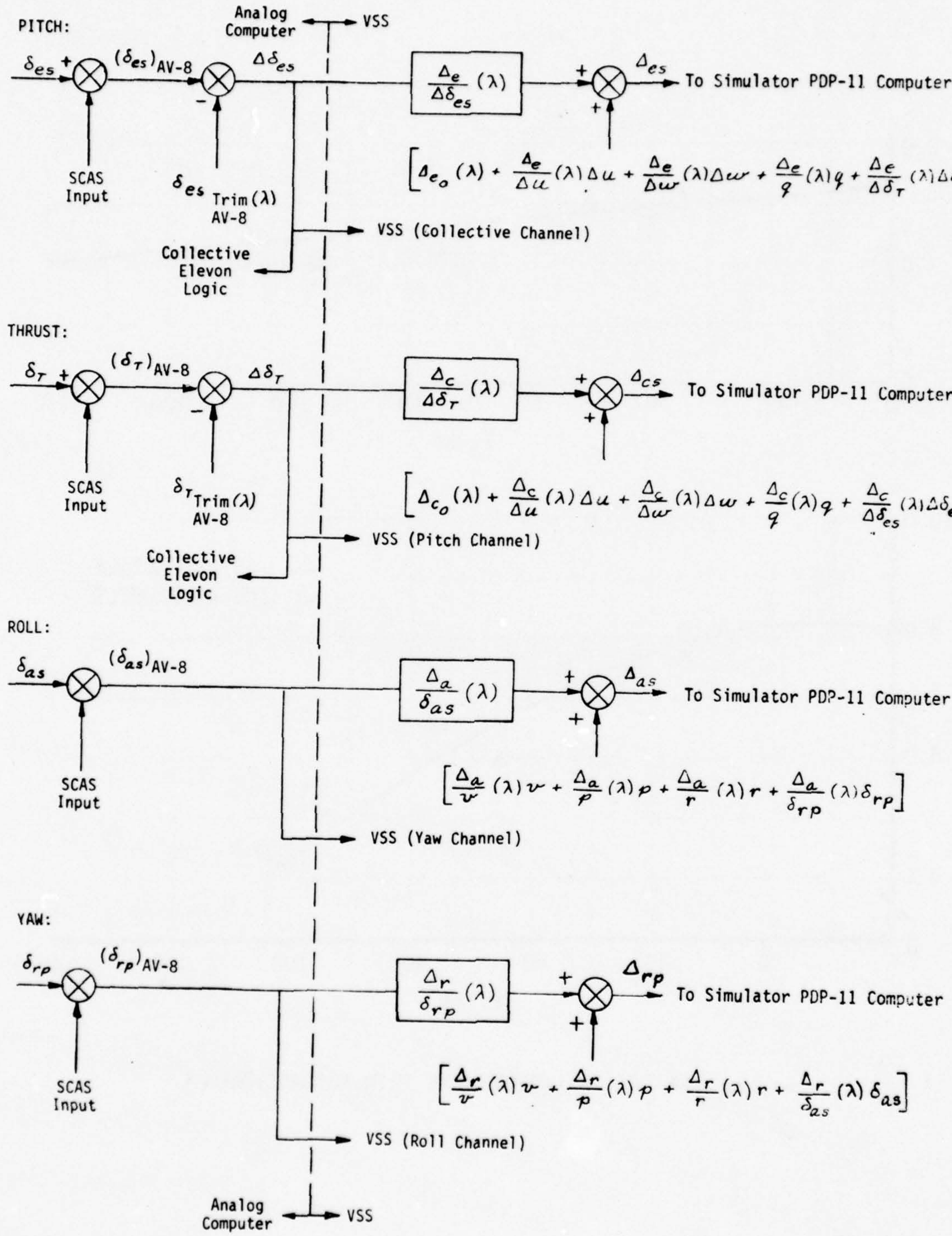


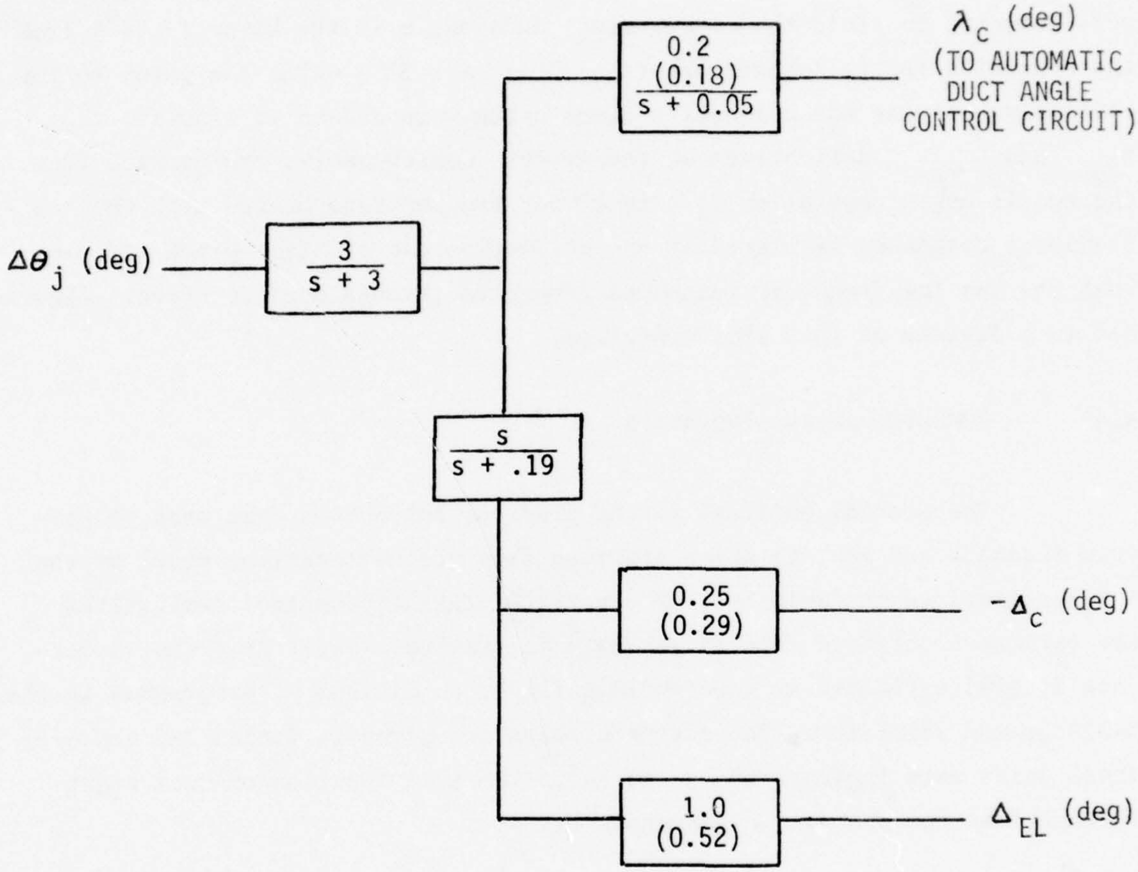
Figure 3-5 AV-8B MODEL MECHANIZATION

collective elevons and collective blade pitch through a washout circuit. The time constant of the running integrator approximated the value of X_u of the AV-8B while the washout time constant was selected to be the value of X_u for the X-22A. The feedforward gains to the automatic duct rotation circuit were selected to yield the proper final duct angle in the hover ($\sim 84^{\circ}$) from the specified initial conditions ($\theta_{j} = 70^{\circ}$; $\lambda = 50^{\circ}$) while the gains to the collective elevons and collective blade pitch were chosen to simulate the X_{θ_j} and Z_{θ_j} derivatives of the AV-8B. Consequently, the command from the nozzle angle controller is effectively frequency-separated with the high-frequency responses simulated by the collective use of blade pitch and elevons and the low-frequency responses generated through duct rotation. Figure 3-6 is a diagram of this implementation.

3.4 COMPUTED AV-8B SIMULATION

The methods outlined in the previous subsection were used to compute feedback and gearing gains starting from the mathematical model of the X-22A summarized in Table 3-4. These X-22A stability/control derivatives are estimates obtained from flight data in previous flight programs (Reference 2) plus estimates at intermediate flight conditions as programmed in the X-22A ground simulator. The computed gains are given in Tables 3-5 and 3-6; these gains were implemented in the X-22A VSS as a function of duct angle through function generators (Appendix V).

A summary of computed longitudinal and lateral-directional time history comparisons between the AV-8B model and the X-22A simulation using the X-22A mathematical model (Table 3-4) and computed gains (Tables 3-5, 6) discussed above is given in Appendix I. As these comparisons show, the computed simulation fidelity was excellent both longitudinally and lateral-directionally at the six flight conditions. Lateral-directionally, the only significant mismatch was in lateral acceleration; this discrepancy is caused by the excellent sideslip match in conjunction with the difference in Y_{β} between the AV-8B and the X-22A. Longitudinally, the only flight condition at which the simulation was not considered too good is 80 Kt;



(for V_o = 65 kts, $\theta_{j_o} \approx 70^o$, $\lambda_o \approx 50^o$; numbers in parentheses indicate gains required for V_o = 105 kts, $\theta_{j_o} = 62^o$, $\lambda_o = 15^o$)

Figure 3-6 NOZZLE ANGLE CONTROL SYSTEM

TABLE 3-4a X-22A GROUND SIMULATOR LONGITUDINAL MODEL

λ		90	67.25	52	42	29.25	15
X_u		-.150	-.168	-.178	-.183	-.188	-.190
Z_u		-.0044	-.130	-.189	-.218	-.252	-.272
M_u		+.015	-.0051	-.0095	-.0098	-.0083	-.0064
X_w		0	-.038	-.033	-.020	+.020	+.115
Z_w		-.12	-.393	-.522	-.574	-.640	-.658
M_w		+.0009	-.0060	-.0168	-.0171	-.0111	-.0045
X_q		0	0	0	0	0	0
Z_q		0	0	0	0	0	0
M_q		+.226	+.068	-.067	-.145	-.315	-.56
$X_{\delta ES}$		-.14	-.313	-.355	-.353	-.299	.176
$Z_{\delta ES}$		-.16	-.095	-.014	+.065	.260	.690
$M_{\delta ES}$		.35	.334	.325	.319	.309	.297
$X_{\delta e}$		0	.337	.563	.69	.91	1.20
$Z_{\delta e}$		-1.5	-1.22	-1.00	-.89	-.69	-.43
$M_{\delta e}$		+.0003	.0115	.0202	.024	.0325	.0427
$X_{\Delta EL}$		-.4	-.37	-.32	-.28	-.20	-.07
$Z_{\Delta EL}$		0	-.15	-.25	-.29	-.35	-.39
$M_{\Delta EL}$		0	0	0	0	0	0

TABLE 3-4b X-22A GROUND SIMULATOR LATERAL-DIRECTIONAL MODEL

λ		90	67.25	52	42	29.25	15	
Y_v		-.124	-.220	-.265	-.288	-.300	-.300	
L'_v		-.0148	-.0284	-.0346	-.0381	-.0396	-.0400	
N'_v		+.0011	+.0011	+.0010	+.0005	-.0002	-.0012	
Y_p		0	0	0	0	0	0	
L'_p		.0698	-.44	-.70	-.869	-.969	-1.062	
N'_p		.0001	-.066	-.099	-.132	-.152	-.178	
Y_r		0	0	0	0	0	0	
L'_r		.0009	.77	1.18	1.46	1.646	1.854	
N'_r		-.17	-.21	-.21	-.195	-.165	-.10	
$Y_{\delta as}$		0	0	0	0	0	0	
$L'_{\delta as}$		.38	.38	.38	.38	.38	.38	
$N'_{\delta as}$		.0427	.047	.050	.0556	.060	.0678	
$Y_{\delta RP}$		0	0	0	0	0	0	
$L'_{\delta RP}$		.095	-.12	-.150	-.143	-.128	-.102	
$N'_{\delta RP}$		.23	.19	.155	.127	.10	.058	

TABLE 3-5 LONGITUDINAL GAINS

λ		90	67.25	52	42	29.25	15
$\Delta E/u$		.043	-.0156	-.024	-.0226	-.031	-.0042
$\Delta E/w$		-.0095	-.040	-.075	-.0733	-.046	0
$\Delta E/\theta$		0	0	0	0	0	0
$\Delta E/q$		.806	.567	.364	.145	-1.000	-2.078
$\Delta C/u$		0	.089	.034	.00127	.038	-.12[illegible]
$\Delta C/w$		.069	.223	.212	.1744	.162	.0669
$\Delta C/\theta$		0	0	0	0	0	0
$\Delta C/q$		0	0	0	0	0	0
$\Delta E/\delta_{ES}$		.657	.70	.712	.729	.75	.833
$\Delta E/\delta_T$		-.104	-.173	-.221	-.227	-.224	-.173
$\Delta C/\delta_{ES}$		.163	.222	.284	.312	.284	-.104
$\Delta C/\delta_T$		1.70	1.90	1.77	1.52	1.02	.358
$\Delta EL/\delta_{ES}$		.173	.021	.164	.345	.84	2.11
$\Delta EL/\delta_T$		-.846	.985	2.42	3.10	3.91	3.98

1) Gains are in computer units and signs (F-GK).

2) q gains are compensated for flight to account for u, w sensor offsets.

TABLE 3-6 LATERAL-DIRECTIONAL GAINS

λ	90	67.25	52	42	29.25	15
$\Delta A/v$	-.041	-.0293	-.0304	-.039	-.053	-.078
$\Delta A/p$	+.546	-.1009	-.289	-.332	-.304	.470
$\Delta A/r$	.108	1.31	1.972	2.463	4.383	3.38
$\Delta R/v$	.028	+.024	+.0227	+.021	+.0155	-.0036
$\Delta R/p$	-.0796	-.154	-.201	-.328	-.201	-.791
$\Delta R/r$	-.576	-.947	-1.22	-1.496	-3.232	-4.24
$\Delta A/\delta_{AS}$	1.35	1.27	1.24	1.21	1.19	1.15
$\Delta A/\delta_{RP}$	-.422	.204	.374	.450	.507	.587
$\Delta R/\delta_{AS}$	-.119	-.155	-.199	-.272	-.367	-.719
$\Delta R/\delta_{RP}$	1.06	1.19	1.45	1.76	2.25	3.92

1) Gains are in computer units, signs (F-GK).

2) p, r gains are compensated for flight to account for v sensor offsets.

as it turned out, the high speed (105 Kt) profile was not investigated in the experiment, and so this flight condition was not encountered.

3.5 ACHIEVED AV-8B SIMULATION FIDELITY

As a means of assessing the validity of the achieved simulation, two Marine AV-8A pilots assigned to the Naval Air Test Center, Patuxent River, Md., flew two flights each in the X-22A during the course of this experiment (Reference 18). Comments concerning the similarity or difference between the X-22A AV-8B simulation and the AV-8A characteristics were tape-recorded during the flights, and summaries given in the post-flight meetings. A summary of most of the comments is given below; if the comments were noticeably different between the two pilots, either both comments are given or the specific comment is called out separately:

1. <u>LEVEL FLIGHT AND CONSTANT SPEED DESCENT</u>

- Pitch and roll stick forces like AV-8A. Throttle controller easier than AV-8A because of armrest.

- Pitch response sluggish at 70 Kt like AV-8A (Anderson). Pitch didn't seem quite the same, but not sure (O'Connor).

- Airspeed control more precise than AV-8A (O'Connor). Airspeed control more difficult than AV-8A (Anderson).

- Roll response like AV-8A.

- Yaw response similar to AV-8A but easier, coordination required but not as much monitoring.

- Glide slope control like AV-8A in pitch.

- Low speed response to disturbances like AV-8A.

- Reacted to crosswind approach like AV-8A.

- Throttle-nozzle controllers further apart than AV-8A (O'Connor).

2. <u>DECELERATION</u>

- Fidelity of simulation good, seemed very similar, felt like AV-8A.

- Airspeed bled off a little more slowly, altitude control was a little easier (Anderson).

3. <u>HOVER</u>

- Control forces, pitch and roll responses like AV-8A.

- Altitude control easier than AV-8A.

- Pedal turns constant rate in X-22A, varying in AV-8A. Pedal reversal not required in X-22A.

- More pitch attitude required to generate velocities than AV-8A.

- More pitch attitude required to counteract wind.

- Feels similar to Harrier in hover except I can hold altitude better (O'Connor). Same degree of difficulty in hover as Harrier — would guess IFR would be more difficult because of attitude change requirement (Anderson).

4. SUMMARY COMMENTS

- Overall simulation good, very similar to Harrier in most respects.

- Simulation was higher fidelity than expected. There is no requirement for a more precise simulation — this is the way to look at the AV-8 IFR capability (Anderson).

In summary, both the analytic comparisons presented in the previous subsections and the pilot flight evaluations of the simulation indicate a high degree of simulation validity was achieved in this experiment. Although the linear AV-8B model represents an approximation to the full-blown AV-8B characteristics, and although perfect replication of all state and acceleration responses was not possible in the simulation, it is correct to say that the dynamic situations that were simulated are representative of a jet-lift VTOL aircraft and were very similar to those of the AV-8A/B class in particular.

Section 4
CONTROL SYSTEMS DESIGN

4.1 SYNOPSIS OF SECTION

The purpose of this section is to describe the control system concepts implemented for this investigation and to summarize the resulting vehicle dynamic characteristics. This experiment, unlike the previous X-22A program (Reference 2), was directed to control/display concepts applicable to a specific vehicle, the AV-8B. Accordingly, both the control laws and their implementation details were configured to be of direct utility to the AV-8B development program. Specifically, the fact that the AV-8B utilizes a mechanical flight control system with limited authority series servos for augmentation tends to preclude the use of high gain augmentation systems because of SCAS actuator saturation. To investigate the tradeoff of control system gain and SCAS actuator displacement, an electrical analog of the AV-8B mechanical flight control system together with limited authority electrical augmentation loops was implemented on the X-22A. Complex systems such as decoupled velocity control, which require independent control of forces, were not considered because the thrust magnitude and angle control systems of the AV-8B do not currently have any servo links. Table 4-1 summarizes the three augmentation system concepts simulated in this experiment.

TABLE 4-1
TASK IV CONTROL SYSTEMS

• Rate Command	-	pitch and roll damping augmentation
	-	directional, automatic turn coordination with pilot selected yaw rate command/ heading hold in hover.
• Rate Command/ Attitude Hold	-	pitch and roll damping augmentation with attitude hold
	-	directional, automatic turn coordination with pilot selected yaw rate command/ heading hold in hover
• Attitude Command	-	pitch and roll attitude stabilized
	-	directional, automatic turn coordination with pilot selected yaw rate command/heading hold in hover.

For the latter two augmentation systems, three levels of attitude stabilization were designed to explore SCAS gain versus SCAS actuator activity tradeoffs. Control sensitivities were initially established at satisfactory values in the sense of MIL-F-83300(Reference 9) but were varied, in the course of the experiment, on the basis of pilot commentary.

The following subsections describe the implementation details of the augmentation systems studied. Subsection 4.5 discusses the sensitivity of SCAS actuator activity to augmentation system type and gain level on an analytical basis. This section concludes with a summary of the control sensitivities employed in this experiment compared to the requirements of Reference 9.

4.2 RATE COMMAND - AVSAS

The baseline configuration for the current investigation is essentially the same as the AV-8B SAS, the major difference being the omission of shaping filters in the rate and lateral acceleration feedback loops. The system, diagrammed in Figure 4-1(a) and (b) employs pitch and roll rate feedback to produce angular rate responses to steady longitudinal and lateral stick commands. The directional axis employs washed out yaw rate feedback and lateral acceleration feedback to augment Dutch roll damping and frequency respectively. An aileron to rudder interconnect (ARI) is also mechanized to minimize pilot required pedal inputs for coordination in turn entries. The ARI gain is scheduled with thrust vector angle such that in hover the interconnect is zero. The washout of the yaw rate feedback is intended to eliminate the requirement for rudder pedal inputs in steady turns. The intent of the directional axis augmentation is to ease pilot workload in turns by providing automatic turn coordination (ATC).

A control option, not included in the actual AV-8B SAS, is a yaw rate command with heading hold directional augmentation system, intended to ease the piloting task in hover. This control system was implemented by feeding back yaw rate and heading angle to the directional controls to achieve

K_q = 16.1 IN/RAD/SEC

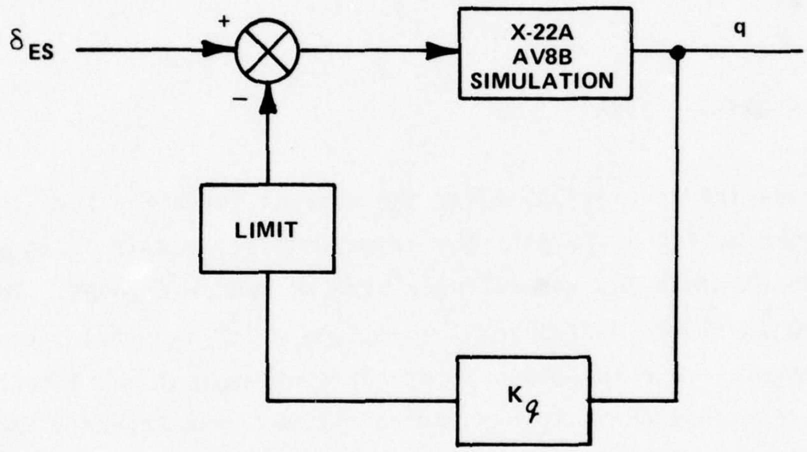


Figure 4-1 (a) IMPLEMENTATION OF AVSAS (APPROXIMATION OF AV8B SAS) – LONGITUDINAL

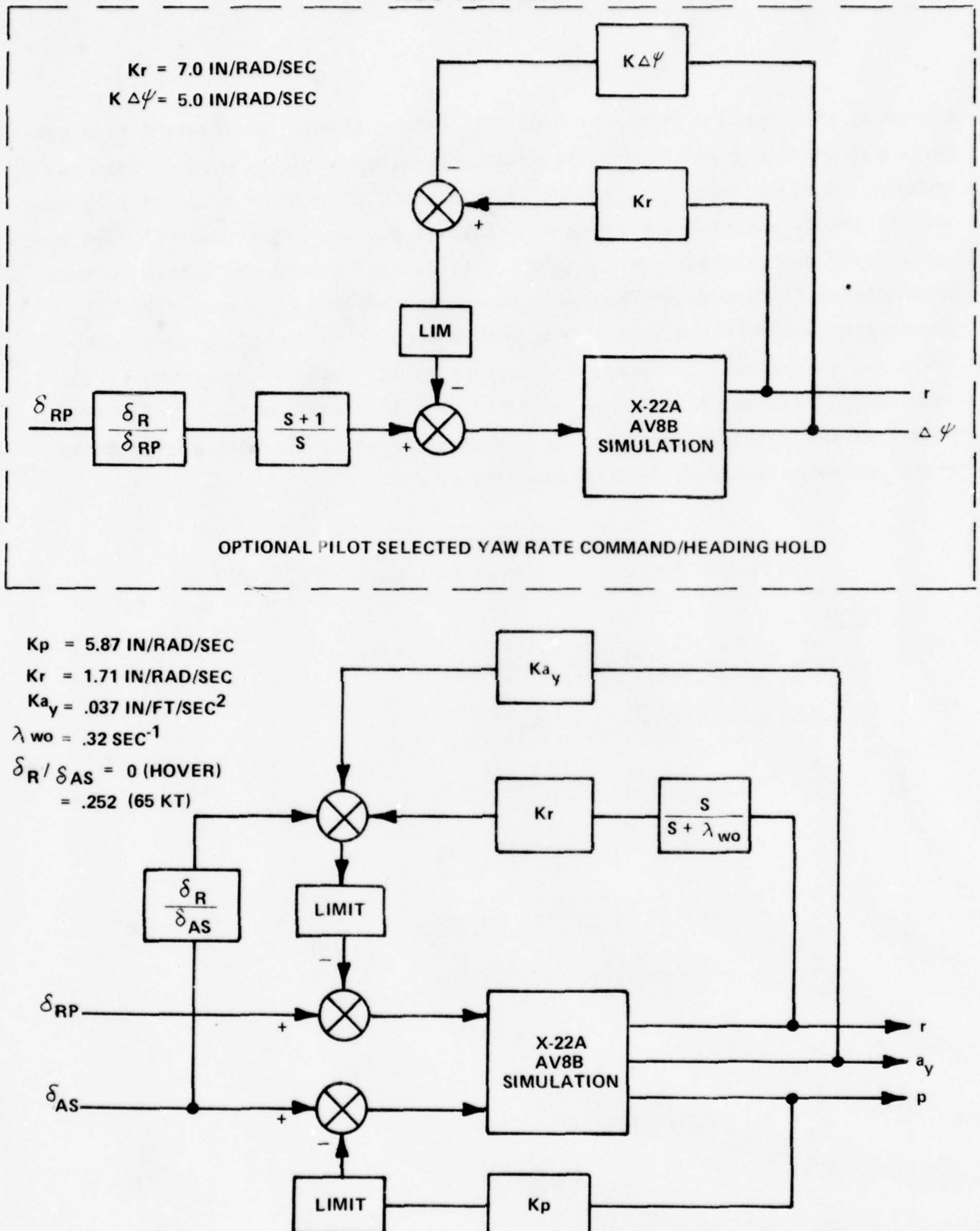


Figure 4-1 (b) IMPLEMENTATION OF AVSAS (APPROXIMATION OF AV8B SAS) – LATERAL-DIRECTIONAL

a heading stabilized directional mode with pedals fixed. An integral plus proportional prefilter was used on the rudder pedal commands to produce rate responses. A pedal force gradient of 14 lb/in. and a breakout force of 9 lb were used to ensure positive centering of pedals (i.e., zero rate command) when the pedal force was relaxed. Simultaneous with switching from the automatic turn coordination (ATC) mode to the yaw rate command/heading hold mode (YRC/HH), the display was switched from an approach-course-up to a heading-up format. Table 4-2 summarizes the transfer functions of the dominant responses to the four cockpit controllers at two flight conditions, corresponding to the end points of the approach trajectories. Complete transfer functions for all the state variables are contained in Appendix I.

TABLE 4-2

AV8B-SAS TRANSFER FUNCTIONS IN FORM $K(1/\tau)[\zeta;\omega_n]$

Hover		
$\frac{\theta}{\delta_{ES}}$	$= \frac{.23(.012)(.14)}{(-.035)(.040)(.15)(3.76)}$	
$\frac{w}{\delta_C}$	$= \frac{-2.55(.0016)(.149)(3.83)}{(-.035)(.040)(.15)(3.76)}$	
$\frac{\phi}{\delta_{AS}}$	$= \frac{0.5(.12)[.77;1.07]}{(3.04)[.33;.18][.77;1.07]}$	YRC/HH
$\frac{r}{\delta_{RP}}$	$= \frac{.225(1.0)(3.13)[.33;.17]}{(3.04)[.33;.18][.77;1.07]}$	YRC/HH
$\frac{\phi}{\delta_{AS}}$	$= \frac{0.5(.019)(.12)(.73)}{(.022)(.74)(3.07)[.32;.16]}$	ATC
$\frac{r}{\delta_{RP}}$	$= \frac{.225(.32)(3.13)[.33;.17]}{(.022)(.74)(3.07)[.32;.16]}$	ATC
65 Knots		
$\frac{\theta}{\delta_{ES}}$	$= \frac{.24(.063)(.52)}{(-.14)(.18)(.49)(4.11)}$	
$\frac{w}{\delta_C}$	$= \frac{-2.26(.051)(.17)(5.89)}{(-.14)(.18)(.49)(4.11)}$	
$\frac{\phi}{\delta_{AS}}$	$= \frac{.480(.32)[.52;.89]}{(.021)(.49)(3.77)[.40;.76]}$	ATC
$\frac{r}{\delta_{RP}}$	$= \frac{.248(.32)(3.84)[.32;.41]}{(.021)(.49)(3.77)[.40;.76]}$	ATC

As can be seen by these transfer characteristics, the pitch and roll rate responses are well damped (time constant less than .3 seconds) in both hover and at the approach speed of 65 knots. In the longitudinal axis, the basic aircraft exhibits an unstable real root at both hover and 65 knots which cannot be stabilized by rate feedback alone. As is typical of VTOL aircraft, the vertical mode in hover ($1/\tau$ = .04) is decoupled from the longitudinal mode.

4.3 RATE COMMAND/ATTITUDE HOLD

This control system was included in the experiment matrix because a similar system has been evaluated by MCAIR in ground based simulations (Reference 10) as an advanced SCAS configuration for the AV-8B. A system of this type will be implemented in the AV-8B. The system as mechanized on the X-22A is illustrated schematically in Figure 4-2(a) and (b). The addition of switched attitude feedback permits rate responses to pitch and roll control commands with attitude retention when the control are released. In both the pitch and roll axes, the attitude feedback signal is filtered by a fast balance and hold network which is, in turn, controlled by the instantaneous stick forces. When the pitch and roll stick forces are greater than 1.5 and .75 pounds respectively, the switch to the integrator in the balance and hold network is closed and the balance and hold network effectively eliminates the attitude feedback over the bandwidth of the aircraft rigid body dynamics. For example in pitch the output of the balance and hold network is $\frac{s}{s+20}\theta \cong 0$. The reference signal at the balance and hold network summing junction is $\frac{20}{s+20}\theta \cong \theta$. Thus the balance and hold network tracks attitude in this mode. When stick forces fall below the reference values, the switch opens and the integrators hold, as a new reference, the attitude at the moment of stick release. With stick force relaxed, the vehicle is attitude stabilized and the attitude feedback signal is $\theta - \theta_{REF}$.

Proper functioning of the rate command/attitude hold system is dependent on suitable choice of force thresholds for the switching logic. Too large a force threshold can be noticeable and bothersome to the pilot since

		1.0 RCAH	2.0 RCAH	
K_q	=	9.2	15.2	IN/RAD/SEC
K_θ	=	4.3	15.0	IN/RAD

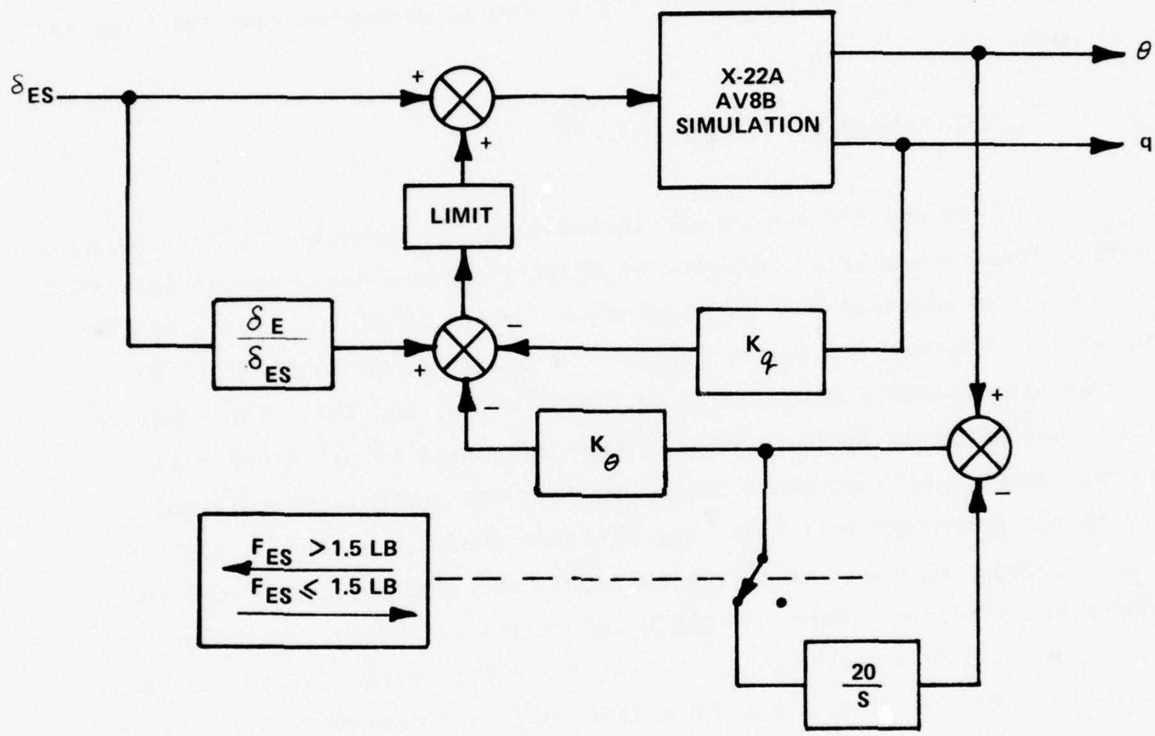


Figure 4-2 (a) IMPLEMENTATION OF RATE COMMAND ATTITUDE/HOLD AUGMENTATION SYSTEM -- LONGITUDINAL

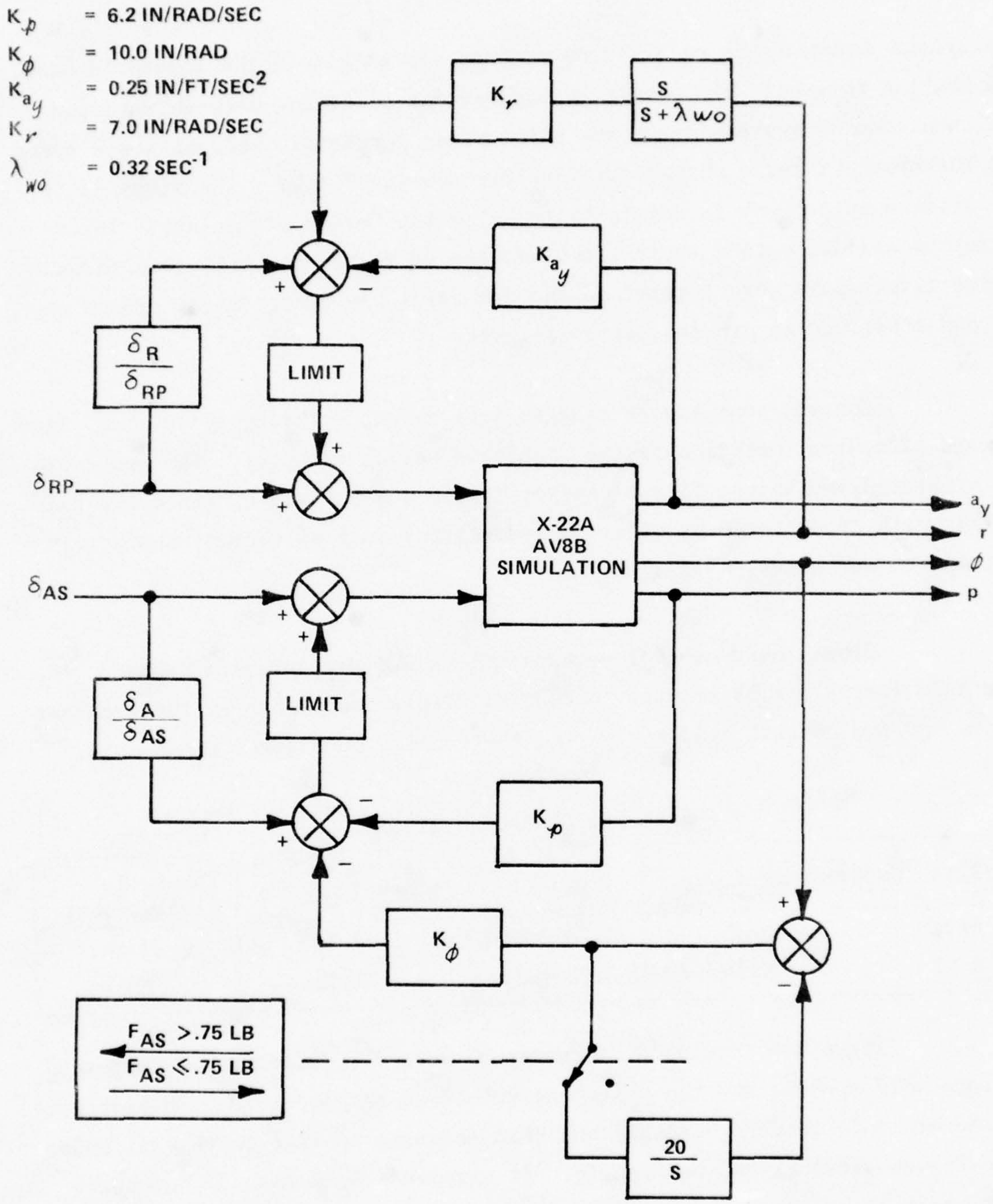


Figure 4-2 (b) IMPLEMENTATION OF RATE COMMAND/ATTITUDE HOLD AUGMENTATION SYSTEM – LATERAL-DIRECTIONAL

the system functions as an attitude command system within the threshold band. Too small a threshold can result in inadvertent switching between rate and attitude command systems since the pilot never completely relaxes stick force and the breakout force characteristics are non-ideal (i.e., the slope of force vs. stick displacement is not infinite below the "breakout" point). This situation will also tend to make the vehicle difficult to trim. The threshold limits cited above were determined through trial and error during ground check-out and confirmed in pre-evaluation flights.

Control sensitivity changes were affected through electrical feed-forward of control position to the simulated series actuator. The gearing of the simulated mechanical flight control system was not varied since the gain of this path is dictated by other considerations such as control characteristics with augmentation off.

Since these control mechanizations are displacement command, the threshold forces can be related to control displacement through the breakout forces and the control gradient. The table below summarizes these data.

TABLE 4-3

FORCE FEEL CHARACTERISTICS

Axis	Breakout Force	Gradient	Threshold Force	Threshold Displacement
Pitch	.5 lb	3.70 lb/in.	1.50 lb	0.27 in.
Roll	.5 lb	3.70 lb/in.	0.75 lb	0.068 in.

There are several differences between the research rate command/ attitude hold systems and the system described in Reference 10. In Reference 10, the attitude feedback balance and hold networks operate in several modes depending on airspeed and bank angle. At airspeeds less than 20 knots the pitch and roll attitude synchronizers are bypassed and fixed attitude references of 8 and 0 degrees respectively are substituted. Since the task in this investigation involved hover over a landing pad, the use of fixed pitch and roll attitude references would have caused the aircraft to drift off the

pad under off-nominal wind conditions due to the longitudinal and lateral drag damping (X_u , Y_v). At airspeeds greater than 25 knots, the Reference 10 system also used a fixed bank angle reference of zero degrees if roll stick force was released at a bank angle less than 7 degrees. Since much of the lateral maneuvering required in the current program involved bank angles of this order of magnitude, it was felt that this mode switching feature would be a nuisance in that small turn rates could not be established with the lateral stick force relaxed. For the reasons cited above, the mode switching features of the Reference 10 system were not implemented for this experiment.

As in the AV-8B SAS, the directional axis is augmented to provide automatic turn coordination. However, the magnitude of the lateral acceleration feedback gain to the rudder is approximately 8 times higher than that of the AV-8B SAS. This gain level was employed to achieve a Dutch roll frequency greater than 1.0 rad/sec since the experiment of Reference 19 indicated that directional stiffness of this magnitude was required for satisfactory control of sideslip in STOL instrument approaches.

Three systems were designed for this experiment although only two, with frequencies of the pitch attitude dynamics equal to 1.0 and 2.0 rad/sec, were evaluated. The roll attitude dynamics were held constant at a natural frequency of 2.0 rad/sec. Selected transfer function characteristics for these systems are presented in Table 4-4. It is noted that the data in this table correspond to the maneuvering situation, that is, rate augmented systems. With the pitch and roll stick forces relaxed, the attitude dynamics are identical to the attitude command systems described in the next section. The electrical feedforward gains for these cases are zero; thus control sensitivities are those of the basic aircraft.

TABLE 4-4

RATE COMMAND/ATTITUDE HOLD TRANSFER FUNCTIONS IN FORM $K(1/\tau)\,[\zeta, \omega_n]$

Hover

Transfer Function	Expression	Mode
$\dfrac{\theta}{\delta_{ES}}$	$= \dfrac{.23(.012)(.14)}{(-.048)(.048)(.16)(2.18)}$	1.0 rad/sec
$\dfrac{w}{\delta_{c}}$	$= \dfrac{-2.55(.0028)(.15)(2.21)}{(-.048)(.048)(.16)(2.18)}$	1.0 rad/sec
$\dfrac{\theta}{\delta_{ES}}$	$= \dfrac{.23(.012)(.14)}{(-.036)(.041)(.15)(3.55)}$	2.0 rad/sec
$\dfrac{w}{\delta_{c}}$	$= \dfrac{02.55(.0017)(.15)(3.61)}{(-.036)(.041)(.15)(3.55)}$	2.0 rad/sec
$\dfrac{\phi}{\delta_{AS}}$	$= \dfrac{.5(.12)[.77;1.07]}{(3.22)[.34;.17][.77;1.07]}$	YRC/HH
$\dfrac{r}{\delta_{RP}}$	$= \dfrac{.225(1.0)(3.31)(.34;.17)}{(3.22)[.34;.17][.77;1.07]}$	YRC/HH
$\dfrac{\phi}{\delta_{AS}}$	$= \dfrac{.5(.0069)(.12)(1.95)}{(.0059)(1.98)(3.20)[.34;.17]}$	ATC
$\dfrac{r}{\delta_{RP}}$	$= \dfrac{.225(.32)(3.31)[.34;.17]}{(.0059)(1.98)(3.20)[.34;.17]}$	ATC

65 Knots

Transfer Function	Expression	Mode
$\dfrac{\theta}{\delta_{ES}}$	$= \dfrac{.24(.063)(.52)}{(-.20)(.22)(.47)(2.49)}$	1.0 rad/sec
$\dfrac{w}{\delta_{c}}$	$= \dfrac{-2.26(4.20)[.99;.11]}{(-.20)(.22)(.47)(2.49)}$	1.0 rad/sec
$\dfrac{\theta}{\delta_{ES}}$	$= \dfrac{.24(.063)(.52)}{(-.15)(.18)(.49)(3.89)}$	2.0 rad/sec
$\dfrac{w}{\delta_{c}}$	$= \dfrac{-2.26(.054)(.16)(5.66)}{(-.15)(.18)(.49)(3.89)}$	2.0 rad/sec
$\dfrac{\phi}{\delta_{AS}}$	$= \dfrac{.50(.33)[.76;1.46]}{(-.0045)(.53)(3.92)[.69;1.41]}$	ATC
$\dfrac{r}{\delta_{RP}}$	$= \dfrac{.248(.32)(4.02)[.33;.40]}{(-.0045)(.53)(3.92)[.69;1.41]}$	ATC

4.4 ATTITUDE COMMAND

This control system was the most sophisticated augmentation system of this experiment. It was included because, in the Reference 2 investigation, it was the augmentation system of lowest complexity capable of producing satisfactory pilot ratings without the addition of control directors to the display information. Furthermore this system requires no additional sensors compared to a rate command/attitude hold system. At question, however, was whether SCAS actuator limits would preclude the use of sufficiently high feedback gains to provide satisfactory stability and control characteristics during the approach and transition to hover. To explore the sensitivity of the magnitude of series servo activity to the feedback gain, three attitude command systems were designed with natural frequencies of the pitch attitude dynamics of 1.0, 1.5 and 2.0 rad/sec with damping ratios in the range of 0.7 to about 1.0. The roll attitude dynamics were held constant throughout the experiment at a natural frequency of 2.0 rad/sec. The directional augmentation was unchanged from that employed with the rate command/attitude hold system. A block diagram of the system mechanization is presented in Figure 4-3(a) and (b) while Table 4-5 below summarizes the primary transfer function characteristics. The control sensitivities for these data correspond to an electrical feedforward gain of zero.

Feedback gains for these systems were calculated to achieve the desired characteristics at the hover flight condition since, in the Reference 2 investigation, the difficulty of the IMC hover task often dominated the pilot rating for the whole approach. It can be seen from the data of Table 4-5 that the feedback gains for the lowest frequency configuration are insufficient to stabilize an aperiodic root of the longitudinal dynamics at 65 knots and the frequency of the attitude mode is approximately half the nominal value. For the remaining configurations, the pitch attitude natural frequencies are essentially the same as in hover although the damping ratios are greater than critical ($\zeta > 1.0$).

		1.0 ACAH	1.5 ACAH	2.0 ACAH	
K_q	=	9.2	12.0	15.2	IN/RAD/SEC
K_θ	=	4.3	9.0	15.0	IN/RAD

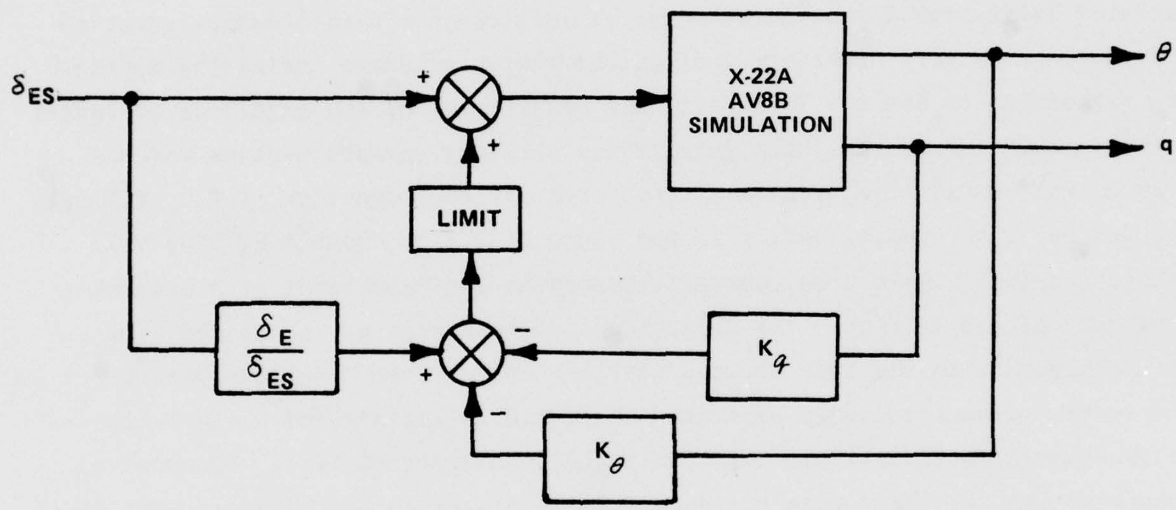


Figure 4-3 (a) IMPLEMENTATION OF ATTITUDE COMMAND SYSTEM – LONGITUDINAL

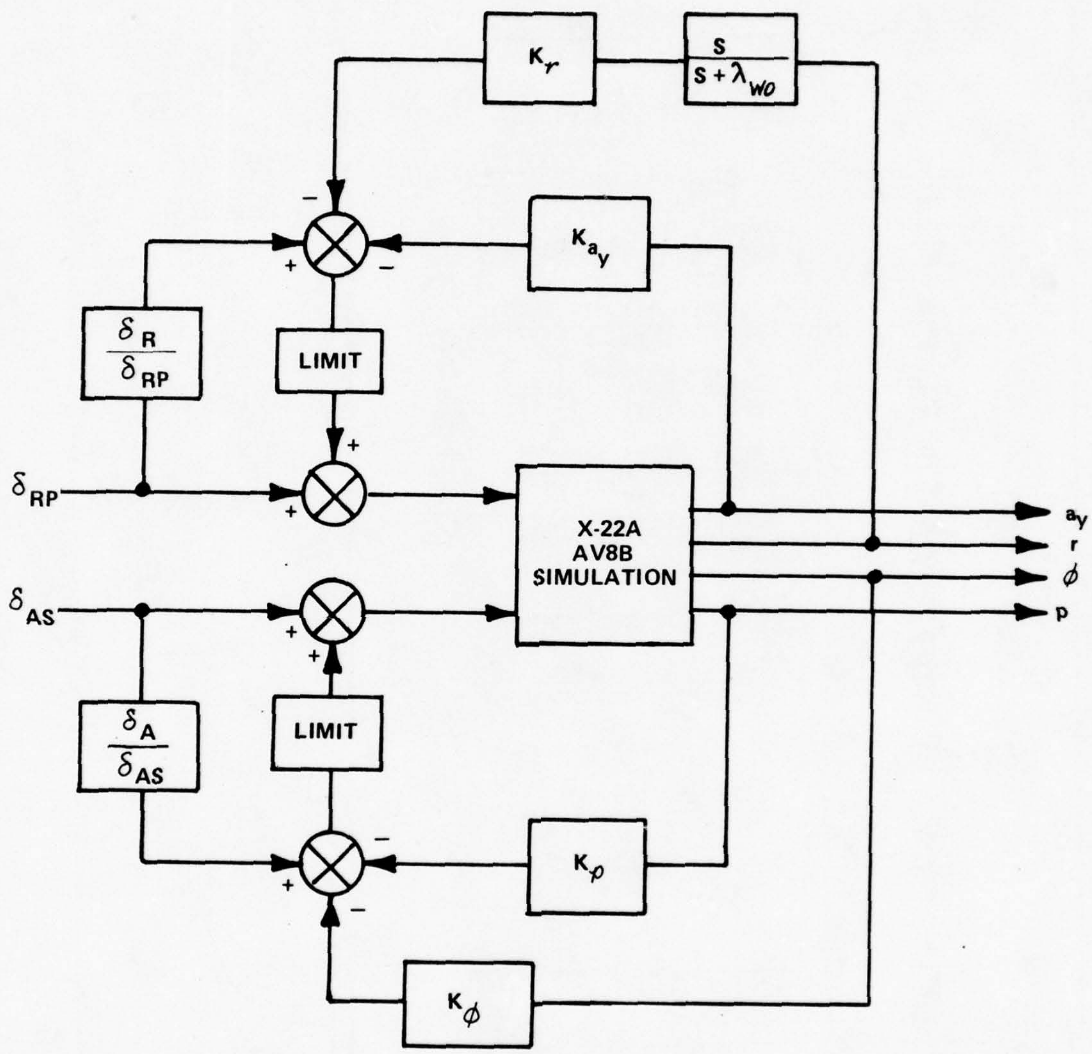


Figure 4-3 (b) IMPLEMENTATION OF ATTITUDE COMMAND AUGMENTATION SYSTEM – LATERAL-DIRECTIONAL

TABLE 4-5

ATTITUDE COMMAND TRANSFER FUNCTIONS IN FORM $K(1/\tau)[\zeta, \omega_n]$

Hover		
$\frac{\theta}{\delta_{ES}}$	$= \frac{.23(.012)(.14)}{(.0062)(.14)(.66)(1.53)}$	1.0 rad/sec
$\frac{w}{\delta_{C}}$	$= \frac{-2.55(.14)(.67)(1.55)}{(.0062)(.14)(.66)(1.53)}$	
$\frac{\phi}{\delta_{AS}}$	$= \frac{.5(.12)[.77;1.07]}{(.14)[.72;2.24][.77;1.06]}$	YRC/HH
$\frac{r}{\delta_{RP}}$	$= \frac{.225(1.0)(.15)[.73;2.24]}{(.14)[.72;2.24][.77;1.06]}$	
$\frac{\phi}{\delta_{AS}}$	$= \frac{.5(.0069)(.12)(1.95)}{(.0068)(.15)(1.92)[.72;2.24]}$	ATC
$\frac{r}{\delta_{RP}}$	$= \frac{.225(.15)(.32)[.73;2.24]}{(.0068)(.15)(1.92)[.72;2.24]}$	
$\frac{\theta}{\delta_{ES}}$	$= \frac{.23(.012)(.14)}{(.0090)(.14)[.98;1.44]}$	1.5 rad/sec
$\frac{w}{\delta_{C}}$	$= \frac{-2.55(.14)[.98;1.46]}{(.0090)(.14)[.98;1.44]}$	
$\frac{\theta}{\delta_{ES}}$	$= \frac{.23(.012)(.14)}{(.010)(.14)[.95;1.86]}$	2.0 rad/sec
$\frac{w}{\delta_{C}}$	$= \frac{-2.55(.14)[.96;1.88]}{(.010)(.14)[.95;1.86]}$	
65 Knots		
$\frac{\theta}{\delta_{ES}}$	$= \frac{.24(.063)(.52)}{(-.031)(1.99)[.96;.53]}$	1.0 rad/sec
$\frac{w}{\delta_{C}}$	$= \frac{-2.26(3.93)[.91;.27]}{(-.031)(1.99)[.96;.53]}$	
$\frac{\phi}{\delta_{AS}}$	$= \frac{.50(.33)[.76;1.46]}{(.28)[.67;1.75][.93;2.02]}$	ATC
$\frac{r}{\delta_{RP}}$	$= \frac{.248(.32)(.47)[.89;2.13]}{(.28)[.67;1.75][.93;2.02]}$	
$\frac{\theta}{\delta_{ES}}$	$= \frac{.24(.063)(.52)}{(.018)(.58)(.87)(2.19)}$	1.5 rad/sec
$\frac{w}{\delta_{C}}$	$= \frac{-2.26(.26)(.46)(4.38)}{(.018)(.58)(.87)(2.19)}$	
$\frac{\theta}{\delta_{ES}}$	$= \frac{.24(.063)(.52)}{(.036)(.54)(1.38)(2.46)}$	2.0 rad/sec
$\frac{w}{\delta_{C}}$	$= \frac{-2.26(.24)(.73)(4.91)}{(.036)(.54)(1.38)(2.46)}$	

4.5 EFFECT OF CONTROL LAW ON SCAS ACTUATOR ACTIVITY

As discussed previously, advanced flight control systems (e.g. attitude command, decoupled velocity command) can significantly reduce task difficulty and display sophistication requirements in VTOL instrument approaches. There exists experimental evidence that these control implementations may also be of benefit from the standpoint of control power requirements, a matter of particular importance for aircraft like the AV-8B which employs bleed air for moment control in jet borne flight. The ground simulator experiment of Reference 20 , for example, indicates that, compared to a rate command system, an attitude command system can reduce control power requirements by 40 percent in roll and 30 percent in pitch. However, in vehicles, such as the AV-8B, which employ limited authority series actuators in the mechanical flight control system for augmentation, the avoidance of saturation of the actuator authority can impose design constraints in conflict with control power and flying qualities requirements.

Consider, for example, Figures 4-4 and 4-5 comparing the rate and attitude command systems implemented as in Figures 4-2 and 4-3. For these systems, control sensitivity is adjusted by means of electrical feedforward and has been selected to provide static responses of 0.1 rad/in. in the case of the attitude systems and .2 rad/sec in. for the rate systems. It can be seen that for both systems, high feedback gains (high pitch damping or natural frequency) are accompanied by increased SCAS amplitudes at high frequency. This trend is associated with the increased electrical feedforward gain required to maintain a constant static response with high feedback gains. At low frequency, the SCAS frequency response for all systems approaches unity gain with a phase angle of 180 degrees. This behavior is attributable to the fact that the AV-8B attitude transfer function approximates at least a type 1 system (one or more poles at the origin). Thus, the control surface displacement required to maintain a steady attitude or rate is nearly zero and the action of the SCAS electrical command is to cancel the pilots mechanical control command. Although both rate and attitude systems appear to have equivalent behavior at low

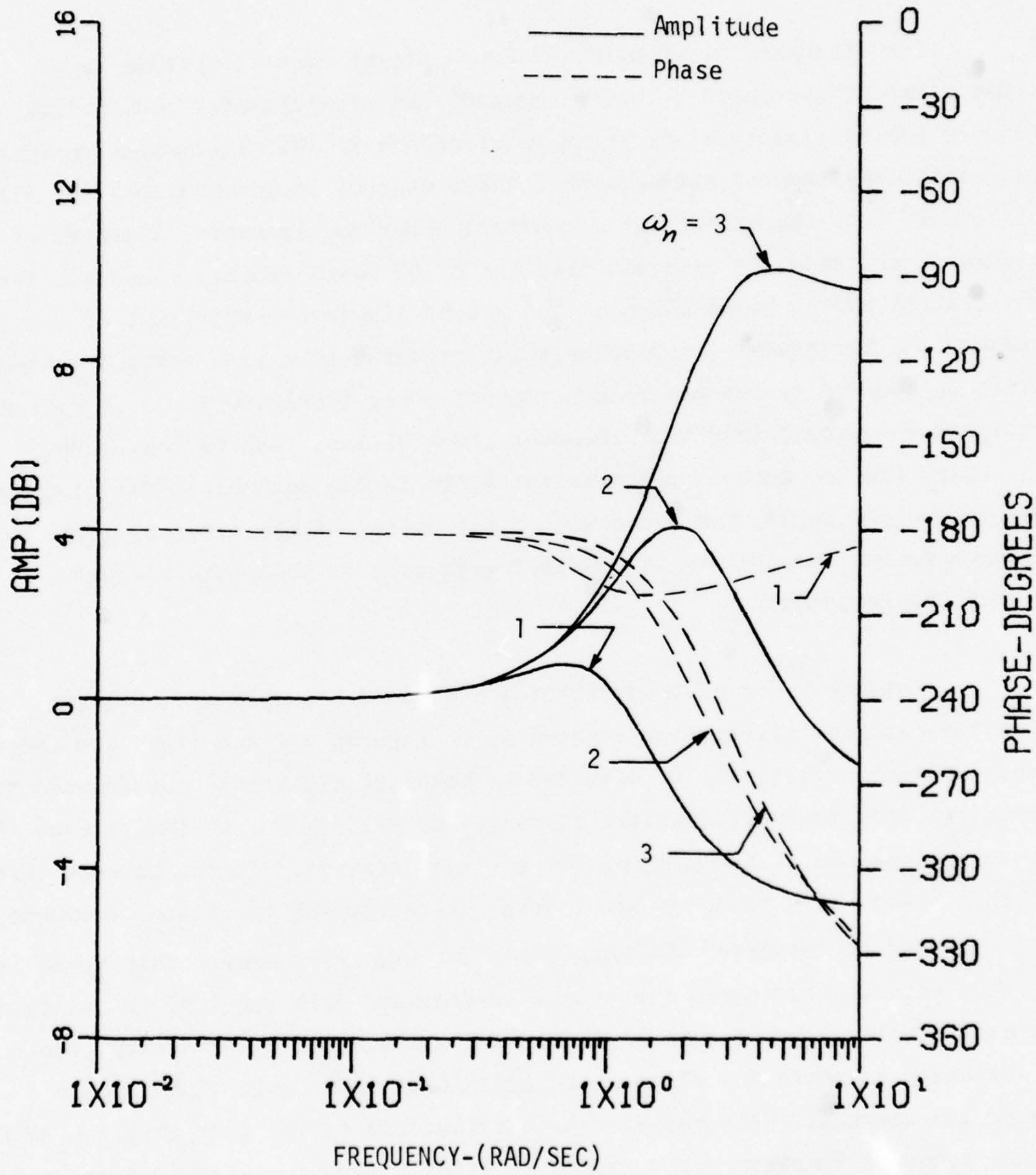


Figure 4-4 SCAS ACTUATOR FREQUENCY RESPONSE FOR ATTITUDE COMMAND AUGMENTATION

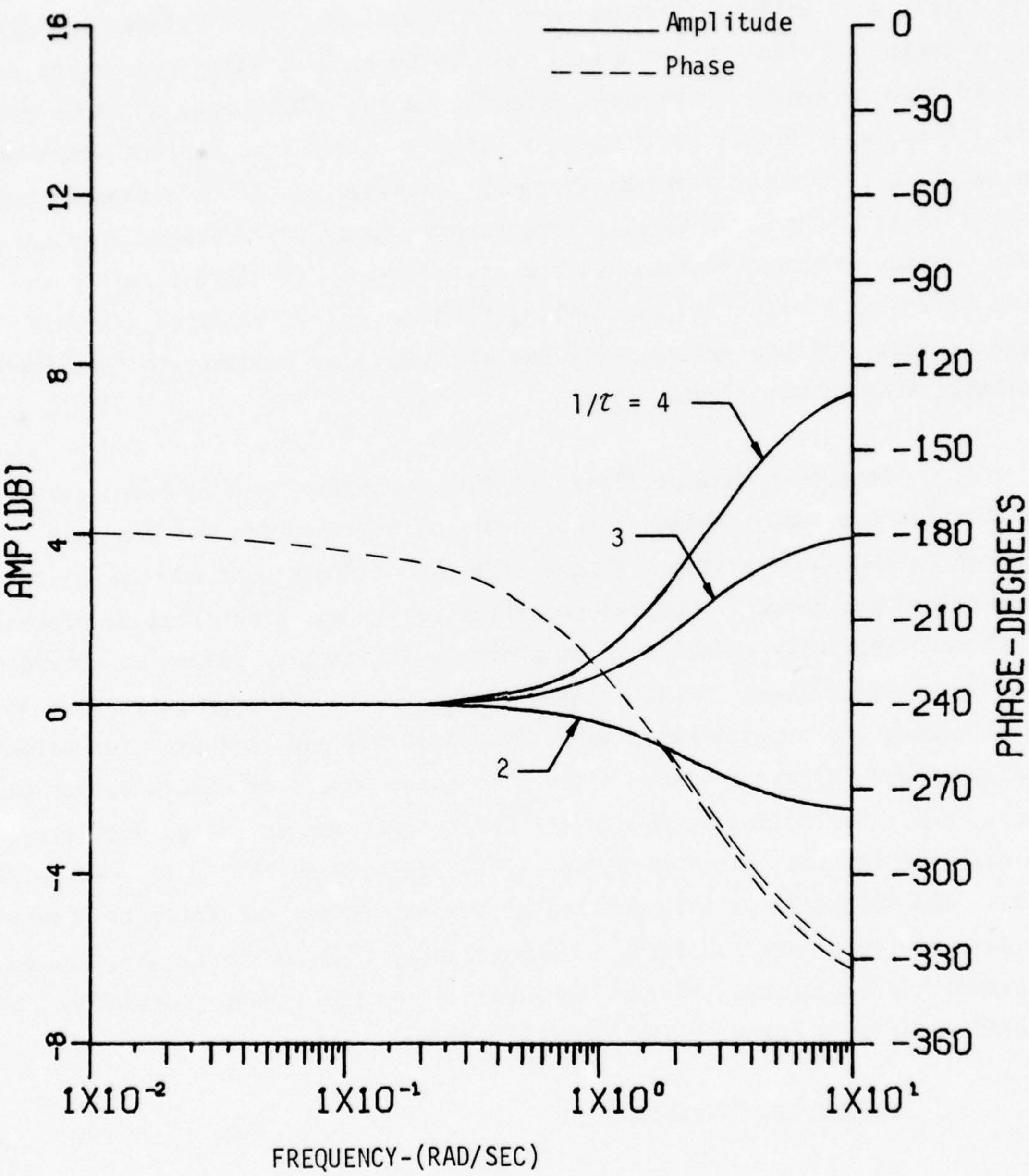


Figure 4-5 SCAS ACTUATOR FREQUENCY RESPONSE FOR RATE COMMAND AUGMENTATION

frequencies, differences in the frequency content of pilot control activity will likely make attitude systems more critical. For rate systems, low frequency cockpit control activity will tend to be minimal since pulse type inputs will be used to generate attitude changes. On the other hand, attitude systems will require significant low frequency activity since steady stick displacements are required to command attitude changes. Although manual or automatic trim devices could be employed to eliminate steady state SCAS actuator displacement, these devices are usually rate limited at low values for flight safety and would have little effect in maneuvering flight. This simplified analysis suggests that attitude systems will exhibit a greater tendency to saturate the available SCAS actuator authority.

To gather data pertinent to SCAS authority requirements versus augmentation type and magnitude, two levels of augmentation for the rate command/attitude hold system and three for the attitude command were designed as described previously. Control sensitivities (i.e., electrical feedforward gains) were initially established at minimum satisfactory values in accordance with the specifications of MIL-F-83300 (Reference 9) although gains were adjusted during the program based on pilot commentary and ratings. For selected configurations, approaches were flown with three levels of simulated authority limits, basic AV-8B limits, double the basic limit and unlimited authority. The basic limits are: pitch ±0.85 in. (20%), roll ±0.59 in. (20%), yaw ±0.71 in. (50%). The objective of this portion of the experiment was first to determine the sensitivity of SCAS activity to augmentation type and level and, second, to determine the degradation in task performance and pilot rating associated with saturation of SCAS actuator limits if it occurs.

4.6 CONTROL SENSITIVITIES

As discussed previously, control sensitivities for each evaluation configuration (with the exception of AVSAS) were initially established to be near the minimum satisfactory values of MIL-F-83300 (Reference 9). For selected configurations, control sensitivities were increased in response to pilot commentary. Reference 2 specifies control sensitivities for each level

of flying qualities in terms of an allowable range of attitude changes per unit control input which must be achieved within one second following an abrupt control input. Table 4-6 summarizes the Level 1 (PR ≤ 3½) sensitivity requirements of Reference 2 compared to those used for the experiment.

TABLE 4-6

COMPARISON OF CONTROL SENSITIVITIES TO REQUIREMENTS OF MIL-F-83300

	Attitude Change in One Second, per Inch					
	Pitch (deg)		Roll (deg)		Yaw (deg)	
	Min	Max	Min	Max	Min	Max
MIL-F-83300	3	20	4	20	6	23
AVSAS	2.6		6.4		5.2	
RCAH 1 rad	3.6		7.7 to 22.4		5.2	
RCAH 2 rad	2.7 to 9.1		4.5 to 16.2		5.2	
ACAH 1 rad	3.3		6.4		5.2	
ACAH 1.5 rad	2.7		7.7 to 22.4		5.2	
ACAH 2.0 rad	3.1 to 7.4		4.5 to 16.2		5.2	

It can be seen from these data that for certain configurations, the control sensitivities employed spanned the Level 1 range of Reference 9 . In general, the highest sensitivity configurations elicited unfavorable comments from the pilots. It was also observed that there appeared to be a relationship between the pitch attitude scaling of the HUD and the pilots perception of control gearing. This point is discussed further in Section 8 together with a comparison of control gains employed in this program with other experimental data.

A complete summary of all evaluation configurations, electrical feedforward gains and resulting control sensitivities is presented in Appendix I.

Section 5
GUIDANCE LAW MECHANIZATIONS

5.1 SYNOPSIS OF SECTION

The purpose of this section is to describe the approach trajectories and guidance laws employed in this flight experiment. The design philosophy follows, to a great extent, that of the previous X-22A program (Reference 2). Some differences in the implementation details were required, however, because the current program was specifically directed to control/display tradeoffs for jet lift VTOL aircraft, in particular the AV-8B. In addition, the use of an AIL Microwave Landing System instead of a tracking radar required the mechanization of additional coordinate transformations in the on-board analog computers to provide the requisite conversion of position data from spherical to rectangular coordinates.

In the following subsections, the modifications to the guidance computations necessitated by the considerations cited above are summarized.

5.2 SIMULATED AV-8B APPROACH TRAJECTORIES AND VELOCITY SCHEDULES

The establishment of nominal approach profiles and airspeed schedules for simulation of AV-8B instrument landings required consideration of both X22-A and AV-8B performance characteristics and aerodynamic limits. This task might be viewed as somewhat speculative since instrument flight procedures for aircraft of this type are still in an evolutionary state. To ensure credibility of the results of the program, McAIR personnel devised two nominal approach trajectories and velocity schedules for evaluation based on estimated AV-8B performance characteristics and extrapolation of current AV-8A terminal area procedures.

The profiles, illustrated in Figure 5-1 are comprised of the following major elements,

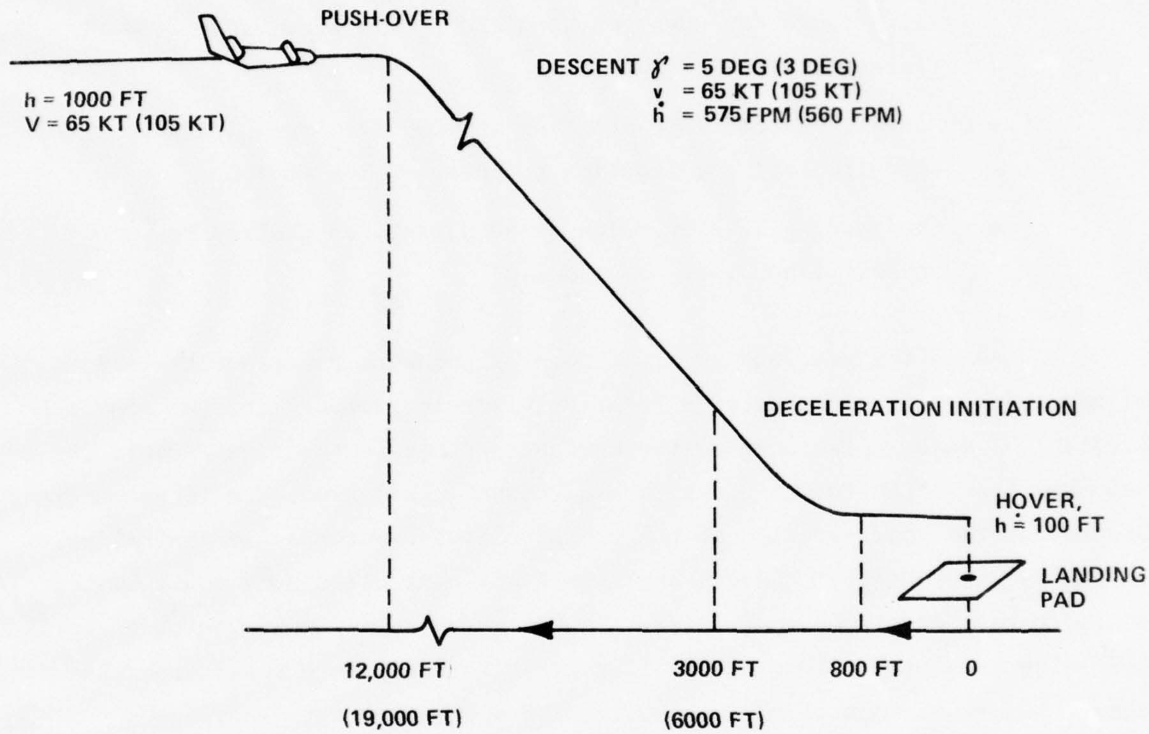


Figure 5-1 RECOMMENDED AV8B APPROACH PROFILES

- level flight localizer acquisition at 65 (alternate 105) knots airspeed
- constant airspeed glide slope acquisition 5.0 degrees (alternate 3.0 degrees) and descent
- one step deceleration (transition to hover configuration) at a range dependent on headwind. Zero wind range 3000 ft (alternate 6000 ft)
- arrest descent rate starting at 1000 ft range, continue longitudinal deceleration to hover at 100 ft AGL.
- no landing but hover/low speed airwork as desired to assess feasibility of landing

As in the previous program, complex guidance requirements were eliminated by the selection of a relatively simple geometry for the approach profile. A major difference in the current program is the requirement for a one step transition to the hover configuration. This procedure is necessary because of the configuration of the cockpit thrust vector angle controller. In the previous program, thrust angle rate was controlled by a thumb switch on the thrust magnitude controller. In the AV-8B, the thrust vector angle is modulated by a proportional controller which is a separate lever from the thrust magnitude controller. Thus, landing approaches with continuous deceleration would likely impose intolerable workloads on the pilot to control speed and flight path angle.

Of the two approach profiles proposed by McAIR, the 105 knot profile is closest to that currently employed in the AV-8A in visual landings. The 65 knot profile is more compatible with inherent X-22A characteristics from the standpoint of matching incremental thrust vector angle (i.e., $Z_{\delta_T}/X_{\delta_T}$). In addition, the performance improvements in the AV-8B compared to the AV-8A make a STOL type 65 knot approach profile very attractive in that the pilot has considerably more time in the approach to stabilize the aircraft in preparation for the transition. Therefore, it was decided to base the experiment matrix on the 65 knot approach profile and to examine only selected configurations in the context of the higher speed profile.

5.3 GUIDANCE SYSTEM DESIGN AND IMPLEMENTATION

The purpose of this subsection is to describe the guidance system equations and implementation for the current program. As in the previous program, the information displayed to the pilot required aircraft position and rate expressed in an earth fixed orthogonal axis system. Through appropriate blending with on-board sensor data and transformation these data are used to generate commands for

- longitudinal velocity as a function of range
- lateral velocity as a function of lateral position
- step transition command as function of ground speed
- vertical velocity and position as functions of range

5.3.1 Estimation of Spatial Positions and Rates

Vehicle inertial position and rate with respect to an earth fixed axis system centered in the landing pad and aligned with the approach course were estimated by complementary filtering of MLS position and aircraft accelerometer signals. As discussed in Appendix V, this processing of the MLS data is necessary because the antenna sweep rate and the resolution, primarily of the range signal, makes the MLS position data too noisy for direct differentiation or display to the pilot.

For implementation on the X-22A the accelerometer signals were compensated for gravitational effects (assuming small pitch and bank angles) and resolved into the earth fixed axis system

$$\begin{bmatrix} \ddot{x}e \\ \ddot{y}e \\ \ddot{z}e \end{bmatrix} = \begin{bmatrix} -\cos\Delta\psi & \sin\Delta\psi & 0 \\ \sin\Delta\psi & \cos\Delta\psi & 0 \\ 0 & 0 & -1.0 \end{bmatrix} \begin{bmatrix} ax - g\theta \\ ay + g\phi \\ az + g \end{bmatrix} \qquad (5\text{-}1)$$

Since the MLS has fixed sensitivity, scaling of the radar position data was selected to provide adequate coverage over the whole approach task. The sensitivities selected were as follows:

TABLE 5-1

DIGITAL RADAR DATA SCALING

	RANGE	ELEVATION	AZIMUTH
WORD LENGTH (BITS)	12	12	12
MAX. SCALE RANGE	4096	4096	4096
PARAMETER RANGE	0 to 10 N.M.	0 to 20 DEG	± 30 DEG
SENS. (PER BIT)	15.17 FT/BIT	4.88×10^{-3} DEG/BIT	1.46×10^{-2} DEG/BIT

The exact equations relating x y z to the radar range, elevation and azimuth are,

$$x = \frac{\Delta x \tan^2 \theta_{MLS} + \sqrt{R^2 (\sec^2 \psi_{MLS} + \tan^2 \theta_{MLS}) - \Delta x^2 \sec^2 \psi_{MLS} \tan^2 \theta_{MLS}}}{\sec^2 \psi_{MLS} + \tan^2 \theta_{MLS}}$$

$$y = x \tan \psi_{MLS} \qquad (5\text{-}2)$$

$$z = (x - \Delta x) \tan \theta_{MLS}$$

Since the solution of these equations was accomplished on the X-22A analog computers, two steps were taken to simplify the equations. The first was to colocate the range/azimuth and elevation transmitters ($\Delta x = 0$) and the second was to employ a second order Taylor series expansion of the trigonometric terms in the transformation equations.

As a result of these simplifications, the resultant equations are,

$$x = R\,(1 - 1/2\, \psi_{MLS}^2 - 1/2\, \theta_{MLS}^2)$$

$$y = R\, \psi_{MLS} (1 - 1/6\, \psi_{MLS}^2 - 1/2\, \theta_{MLS}^2) \qquad (5\text{-}3)$$

$$z = R\, \theta_{MLS} (1 - 1/2\, \psi_{MLS}^2)$$

Additional processing of MLS data (compared to the previous program) was required because the position data of the MLS is expressed in spherical coordinates (range, elevation, azimuth). As can be seen in Figure 5-2, the elevation and range/azimuth scanning beams sweep out planes which pass through their respective antenna sites. The MLS provides coded position data each time the aircraft receiver is illuminated by the microwave beams. Therefore the MLS is a sampled data system whose rate is determined by the antenna sweep rate, in this case, 4 Hz.

Table V-3 of Appendix V compares the accuracy of equations (5-3) to the exact expressions. The errors are a maximum at the extremes of elevation and azimuth coverage. However the nature of the approach trajectory tends to preclude large simultaneous azimuth and elevation angles. As can be seen from the table, under conditions representative of a nominal approach trajectory, the errors are negligible.

To minimize noise and compensate for the sample rate of the MLS complementary filtering of position and acceleration signals was performed to achieve smoothed estimates of ground referenced position and velocity. The filter transfer functions are summarized in Appendix V. As in the previous program, application of Kalman filter theory to the estimation of filter characteristics leads to filter break frequencies which are too low from the standpoint of settling time from the onset of MLS lock-on. As a compromise, a filter break frequency of .35 rad/sec was selected which resulted in a settling time of approximately 15 seconds. Processing real flight data through filters with break frequencies ranging from 0.175 to .5 rad/sec indicated that below about .35 rad/sec the noise on the filtered estimates was fairly insensitive to filter break frequency.

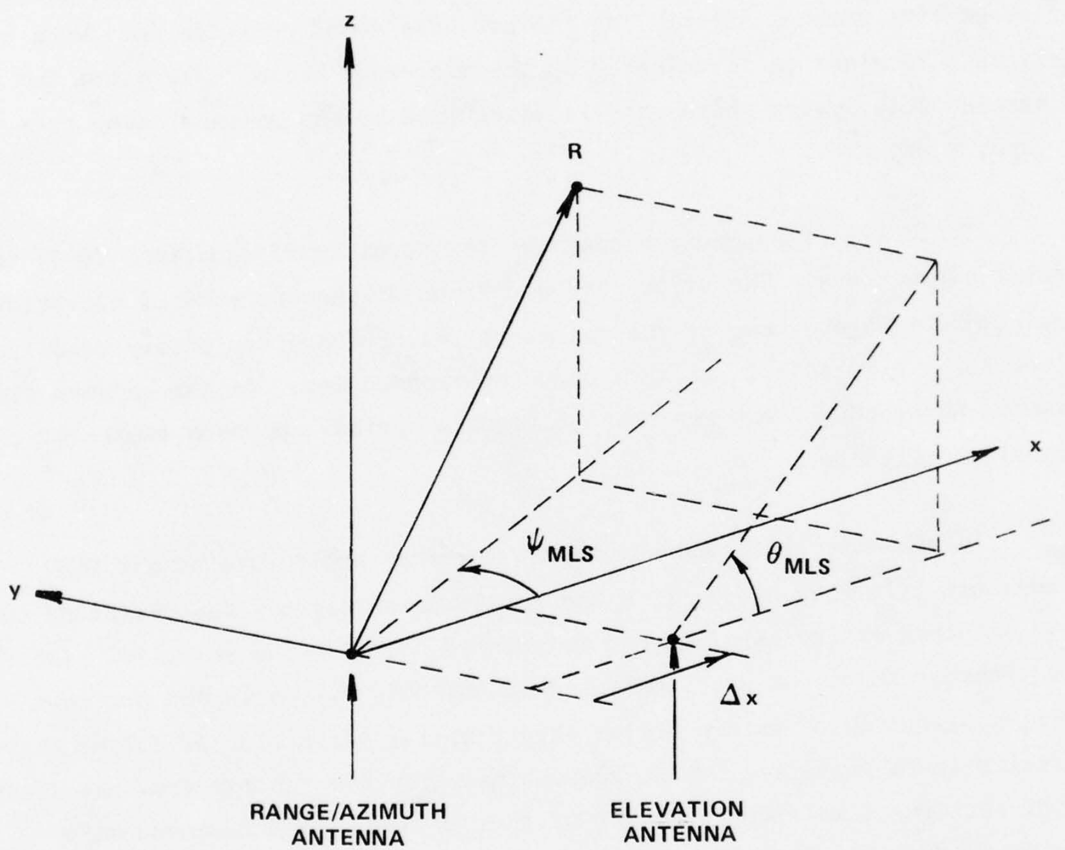


Figure 5-2 MICROWAVE LANDING SYSTEM GEOMETRY

5.4 HORIZONTAL PLANE VELOCITY COMMANDS

A fundamental difference between the current and the previous investigation is the nature of the transition from the approach to the hover configuration. Because of the configuration of the thrust vector controls of the AV-8B, the transition to hover is performed in a step-wise manner; the ensuing deceleration is largely determined by the vehicle's drag damping although modulation of pitch altitude by the pilot can be used to modify the deceleration.

Because of this fact, the timing of transition initiation is critical. If thrust vectoring is early, the vehicle will tend to stop short of the landing pad and will require nose down pitch altitude commands by the pilot to force the vehicle to the pad. Conversely, late vectoring will tend to produce overshoots with attendant nose-up commands by the pilot to increase the vehicle deceleration. The presence of headwinds or tailwinds further complicates the problem because the range for thrust vectoring is a function of the along-track wind magnitude.

A practical and proven solution to this problem was to adopt a guidance logic similar to that employed in the previous program together with a modification of the ITVIC thrust vector command indicator for transition initiation.

The procedure employed was to treat the approach guidance commands in two parts, pre-transition and post-transition, exhibiting the following characteristics:

- Airspeed command during localizer and glideslope acquisition and tracking (pre-transition)
- Course or heading command compensated for along-track and cross-track wind components (pre-transition)
- At transition, smooth undetectable change to ground referenced commands
- Ground velocity commands after transition

The development of the guidance equations to achieve these objectives is described in detail in Reference 2. In the subsections to follow, the relationships employed are summarized and where necessary, differences with respect to the previous program are noted.

5.4.1 Pre-transition Commands

The generation of airspeed and course commands compensated for wind components requires both ground referenced position and velocity and airspeed components. The former measurements are the output of the complementary filters discussed previously. Airspeed data for this program were provided by LORAS airspeed sensors mounted on the nose boom and the vertical fin. The LORAS airspeed sensor is ideally suited for VTOL applications first because the output is linearly proportional to velocity and second because resolution of the total velocity vector into two aircraft body axis components is accomplished within the sensor. These characteristics minimize airspeed sensor data processing requirements although smoothing of the LORAS data was performed for use in the guidance equations (see Appendix V).

The command situation for the landing approach is shown schematically in Figure 5-3. At constant airspeed, u_c, it is desired to follow a commanded course, Γ_c such that the aircraft reaches the approach centerline ($y_e = 0$). As in the previous program the course command employed was

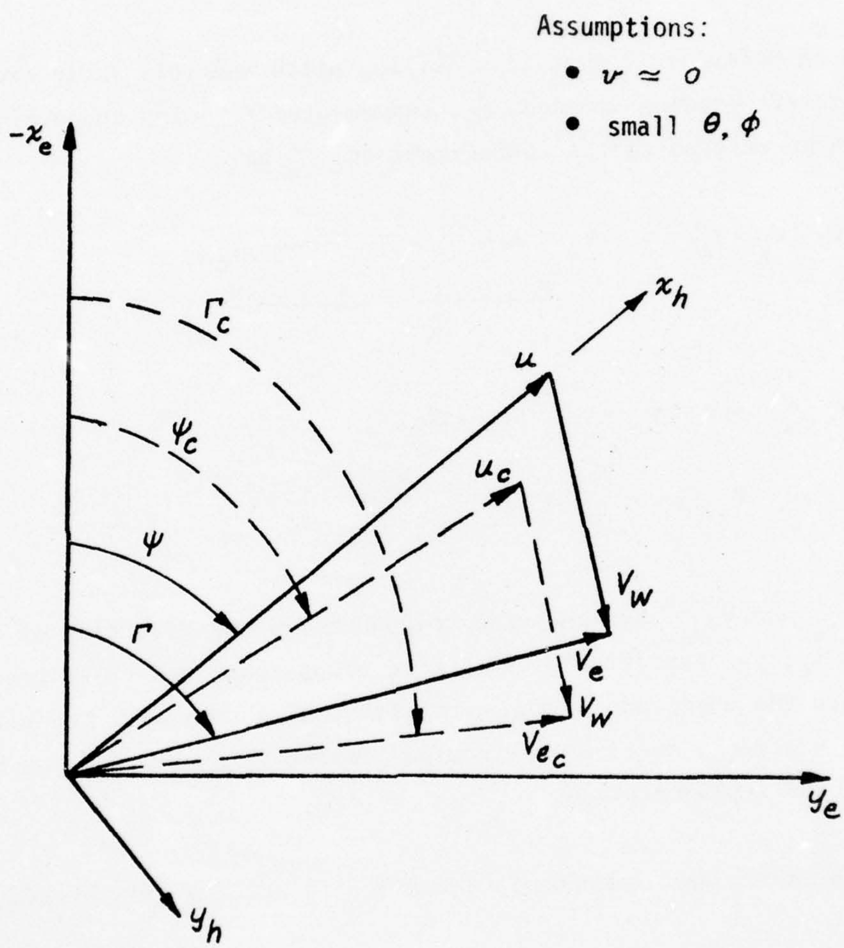


Figure 5-3 COMMAND VELOCITIES FOR AIRSPEED/COURSE TRACKING

$$\Gamma_c = K_\Gamma \hat{y}_e \qquad K_\Gamma = -.030 \text{ deg/ft, 65 Kt approach}$$
$$\Gamma_c \text{ limited at } 45°$$
$$K_\Gamma = -.018 \text{ deg/ft, 105 Kt approach}$$
$$\Gamma_c \text{ limited at } 30°$$

It is shown in Reference 2 that if sideslip, pitch and roll angle are small, then the aircraft heading command, ψ_c, compensated for wind and vehicle airspeed can be related to the course command, Γ_c by

$$\sin(\psi_c - \Gamma_c) = \frac{-V_{w_{x_e}} \sin \Gamma_c - V_{w_{y_e}} \cos \Gamma_c}{u_c} \tag{5-4}$$

If Γ_c and $\psi_c - \Gamma_c$ are small

$$\psi_c \cong \left(1 - \frac{V_{w_{xe}}}{u_c}\right) \Gamma_c - \frac{V_{w_{ye}}}{u_c} \tag{5-5}$$

$V_{w_{xe}}$ and $V_{w_{ye}}$ are the wind components in the direction of approach course axes x_e, y_e respectively. Positive along-track and cross-track winds tend to reduce the magnitude of the aircraft heading command. The along-track wind, in effect, modifies the course command gain K_Γ and has been neglected in the implementation.

Expressing the commands in the aircraft heading axis system

$$\begin{aligned} \dot{x}_{h_c}\big|_{BS} &= u_c \cos(\psi_c - \psi) + V_{w_{xh}} \\ \dot{y}_{h_c}\big|_{BS} &= u_c \sin(\psi_c - \psi) + V_{w_{yh}} \end{aligned} \tag{5-6}$$

Assuming small tracking errors, it is shown in Reference 2 that

$$\begin{aligned} \dot{x}_{h_c}\big|_{BS} &= u_c + \hat{\dot{x}}_h - u = \hat{\dot{x}}_h - \Delta u \\ \dot{y}_{h_c}\big|_{BS} &= u_c K_\Gamma \hat{y}_e - \hat{\dot{y}}_e + \Delta u \sin\psi + \hat{\dot{y}}_h \end{aligned} \tag{5-7}$$

These equations are the ground velocity commands to provide a constant airspeed approach to the approach course centerline. Small angle approximations have been introduced to facilitate implementation on the aircraft analog computers. For the approach course geometry of this investigation, the errors introduced are small and approach zero as the approach course centerline is reached.

Since display presentations in an approach course up format were a selectable pilot option, these commands were generated by a co-ordinate transformation.

$$\begin{aligned} \dot{x}_{e_c}\Big|_{BS} &= -\dot{x}_{h_c}\Big|_{BS} \cos\psi + \dot{y}_{h_c}\Big|_{BS} \sin\psi \\ \dot{y}_{e_c}\Big|_{BS} &= \dot{x}_{h_c}\Big|_{BS} \sin\psi + \dot{y}_{h_c}\Big|_{BS} \cos\psi \end{aligned} \qquad (5\text{-}8)$$

To summarize, prior to transition, a constant airspeed command and an aircraft heading command, compensated for cross-track wind component are computed. The commands are transformed and displayed to the pilot as ground referenced velocity components to eliminate transients upon switching to ground speed commands at the initiation of transition.

5.4.2 Switching Logic and Post-Transition Commands

At the switching point (transition command) ground velocity parallel to the approach course centerline line is commanded as a two segment linear function of range with deceleration to zero velocity over the landing pad. The ground velocity function implemented on an X-22A analog computer function generator is illustrated in Figure 5-4. The linear velocity gradient with range provides an exponential deceleration with time. The increased gradient near hover decreases the effective time constant near the hover pad to speed the approach to hover. The lateral command is scaled to be consistent with the course command prior to switching.

$$y_{e_c}\Big|_{AS} = K_f\,\hat{y}_e \qquad (5\text{-}9)$$

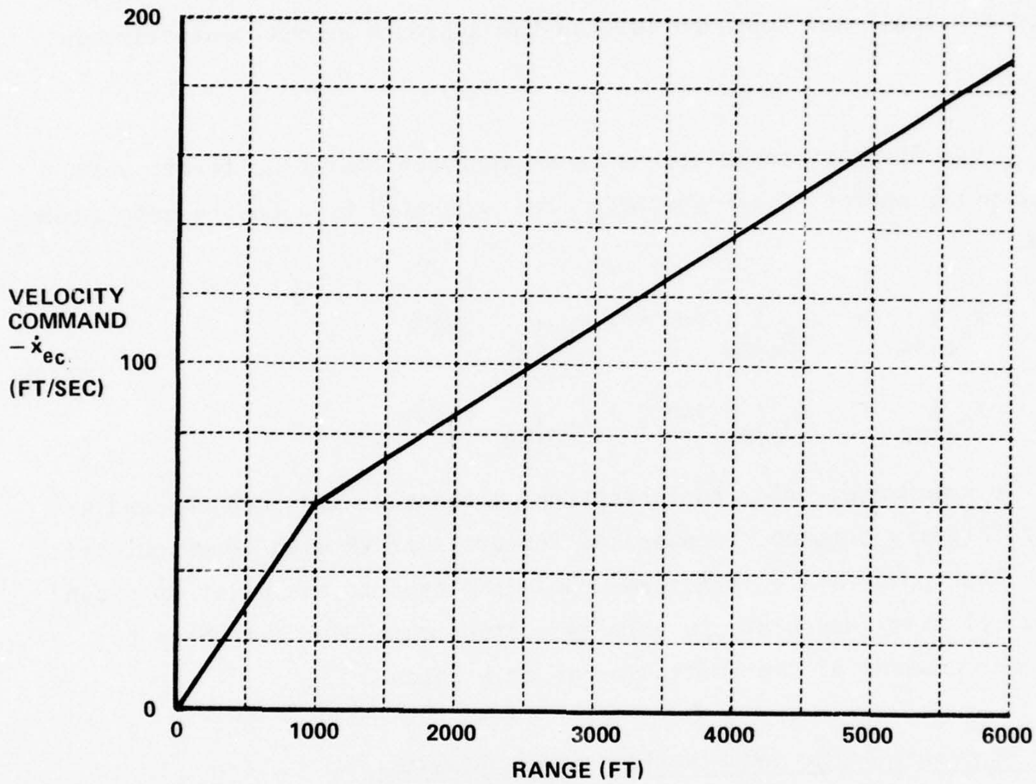


Figure 5-4 DECELERATION PROFILE

where $K_1 = -.057$ ft/sec/ft

$\dot{Y}_{e_c}$ limited to 85 ft/sec

This implementation serves the dual purpose of providing the deceleration commands "after switching" and also of defining the point at which the switching of command logic from airspeed/heading to ground speed component tracking takes place. To provide the information which triggers the logic switching, the aircraft's measured ground speed in the heading-up axis system ($\hat{\dot{X}}_h$) is continuously subtracted from the zero-wind command:

$$\dot{X}_{h_c}\Big|_{\substack{ZERO\\WIND}} = \dot{X}_{h_c}\Big|_{AS} = -\dot{X}_{e_c}\Big|_{AS} \cos\psi + \dot{Y}_{e_c}\Big|_{AS} \sin\psi$$

$$\dot{X}_{h_c}\Big|_{AS} - \hat{\dot{X}}_h \triangleq \epsilon_{\dot{X}_h} \tag{5-10}$$

If there is a headwind component along the desired course, this difference will be greater than zero until the commanded ground speed starts to decrease beyond the zero wind transition initiation point. After the error is reduced to zero, the aircraft must decelerate following the ground speed commands to arrive at the hover point with zero speed relative to the ground. By following the ground speed commands starting closer in, the same deceleration profile is required regardless of headwind.

The logic switching point was therefore determined by:

$$\dot{X}_{h_c}\Big|_{AS} - \hat{\dot{X}}_h = \epsilon_{\dot{X}_h} \Longrightarrow 0$$

The implementation consisted of monitoring this signal continuously after MLS acquisition; when it first became zero, relays were tripped which switched the signals available for display from the "before switching" values to the "after switching" values. Hysteresis was deliberately introduced in the relays to ensure that "flip-flopping" of the command switching did not occur.

5.4.3 Configuration Change Command

As discussed previously, the configuration of the AV-8B thrust vector and thrust magnitude controls do not allow continuous decelerating transitions to be performed. Although jet left VTOLS are more flexible than other types of VTOLS (e.g., tilt rotors, ducted propellors) from the standpoint of allowable transition corridors, considerations of fuel consumption and engine time limits at high thrust settings favors transitioning to fully jet borne as close to the landing pad as possible. In the current program, an essentially open loop one step transition to the hover configuration was employed with the zero wind transition range and the ensuing velocity command schedule selected for compatibility with the AV-8B drag damping characteristics.

The transition was performed manually by moving the thrust vector lever to the hover stop. The transition range was determined by the logic switching point of the guidance system. At the range where $\epsilon_{\dot{x}_h}$ goes to zero, the ITVIC light was switched on as the transition command and a symbol on the HUD flashed until the command was executed. Transition could have been effected automatically under control of the guidance logic. However, since the purpose of the program was to explore minimum complexity control/display combinations this additional complexity was eschewed. It is likely that automating the one step transition would have little impact on pilot workload or rating.

It is noted that as mechanized for this program, the nozzles were always vectored to the hover stop at transition. Thus the vehicle attitude in the hover was a function of the along track winds, nose up for headwinds, nose down for tailwinds. An additional control mechanization to automatically stop the nozzle rotation so as to maintain a constant attitude in hover, regardless of winds, might have eased pilot workload in the terminal portion of

the approach and in hover. However, pilot commentary (See Appendix II) indicate no apparent difficulty with holding nose down attitude to hover in headwinds. Tailwinds caused considerable difficulty with the nose up attitudes required but to control attitude in the presence of tailwinds would require duct rotation significantly beyond the current hover stop, a capability which the X-22A does not possess.

5.5 VERTICAL PLANE COMMANDS

Since both status and control director information was required for the display formats to be investigated on this program, commands for both vertical position and rate were mechanized. The profile was described in Section 5.2. In the vertical plane the approach is comprised of level flight at 1000 feet AGL followed by a 5 degree descent to 100 ft AGL. Figure 5-5 presents the glide slope angle and altitude commands mechanized on the X-22A analog computer function generators. Discontinuities in the altitude profile were minimized by "rounding" the corners to ease the pilots control task during transitions from level flight to descent and vice-versa.

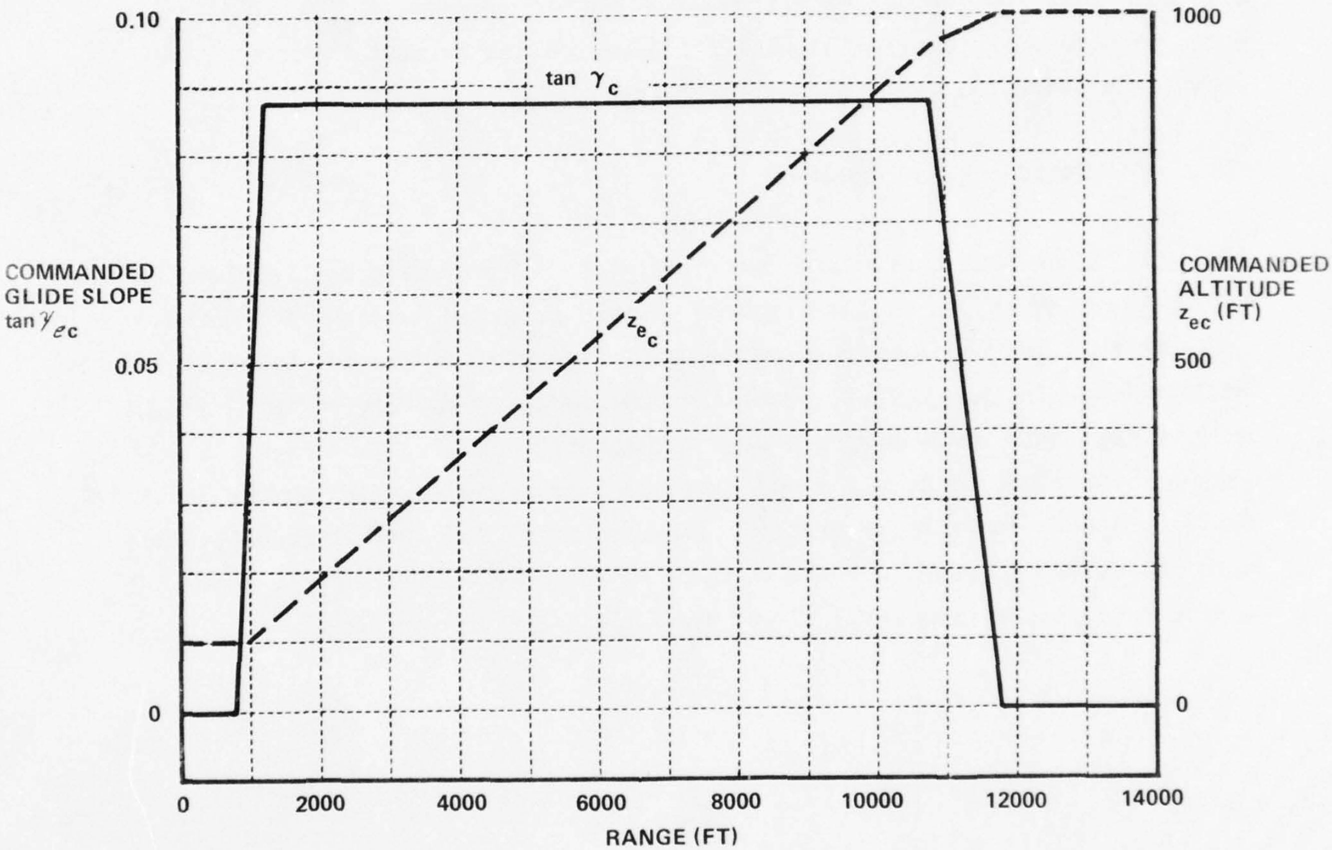


Figure 5-5 SUMMARY OF VERTICAL PLANE COMMANDS

Section 6
DISPLAY DESIGN

6.1 SYNOPSIS OF SECTION

One of the two major variables of this experiment was displayed information and format. The purpose of this section is to describe the formats that were designed and the reasons behind their selection. Since a major influence on the format designs was the information content and design philosophy of the displays investigated in the previous X-22A experiment, the first subsection presents a brief summary of these aspects taken from Reference 2. The next subsection reviews the head-up format proposed for the AV-8B, and relates the previous X-22A experience to the information content on this format; the succeeding subsection then describes a series of changes to this format for investigation in the experiment. Formats based on head-up presentation of the Reference 2 displays are described in the next subsection, and their relationships to the first set noted. The final section summarizes the design of the control director logic for applicable formats.

6.2 REVIEW OF DISPLAY INFORMATION AND DESIGN PRINCIPLES

In the context of the previous X-22A experiment, display "sophistication" (the vertical axis on Figure 1-1) comprised a hierarchy of generic information levels. The intent was to examine the effects on pilot rating of discrete, consistent increases in visually-presented data related to the decelerating instrument approach task, both to determine fundamental information requirements and to evaluate the interplay of these requirements with control system complexity. Previous studies which attempted to define information requirements for the VTOL instrument task (References 21, 22, 23) generally concluded that conventional electromechanical instruments would not be suitable because of the high mental workload associated with gathering and interpreting the displayed data; the need for integrated electronic displays was suggested in Reference 21 and implied by the results of both the NASA

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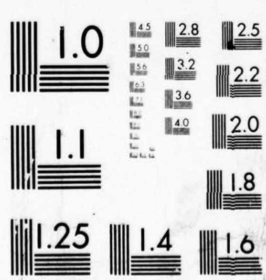

MICROCOPY RESOLUTION TEST CHART
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VALT (Reference 8) and X-22A ground simulator (Reference 24) experiments. For this reason, an electronic (CRT) head-down display unit with variable display format was developed for the Task III experiment; the flexibility afforded by this programmable display then permitted the development of different formats to represent increases in generic information levles as an experimental variable.

Recall from Section 2 that the pilot's control task for the instrument deceleration is, qualitatively, (1) to stabilize and control aircraft attitudes, (2) to command, in conjunction with configuration changes or other translational controls such as thrust or direct lift, translational velocities either, (3) to follow prescribed velocity profiles, and/or (4) to integrate for comparison with translational position commands. Working backwards, one might then hypothesize increasing levels of displayed information consistent with aiding the required loop closures:

- Provide only translational position and commands. All inner loop closures to be made either implicitly through estimating motions of symbols on display or indirectly through force and motion cues.

- Add translational velocity and commands. Only innermost attitude command loops now require implicit or indirect information.

- Add attitude information. Only angular rate stabilization loops now require implicit or indirect information.

- Add control command information. Ideally, no implicit or indirect information is required: the pilot may act as a pure gain to null the displayed control commands.

Although perhaps artificial, this ordering by loop closures provides a rational basis for hypothesizing a reduction in pilot workload as a function of

increasing levels of displayed information. For display design in practical applications, this hypothesized reduction in workload must be balanced against the increasing cost of deriving the additional levels of information from more sophisticated sensors through more complex data processing; hence, if we consider the loop-closure ordering in this light, consistent and discrete groups of information that address this cost tradeoff can be formulated.

Specifically, the attitude information (pitch, roll, heading) may be assumed as given data for all cases: it is well recognized that knowledge of attitude status is a prerequisite for instrument flight if only as a monitor, and this information is essentially part of any aircraft's basic display package. The display of position in three dimensions relative to the approach course, glide slope, and landing pad (commanded positions) requires a relatively simple guidance system (e.g. ILS plus DME) and minimal onboard data processing, and hence is the least expensive information to provide. Adding translational velocity information requires either more sophisticated guidance and/or additional airborne data processing to determine ground-referenced velocites: additional cost is therefore incurred. Finally, control command (i.e. director) information requires even more complex onboard data processing to derive the signals required to drive the individual director elements. On this basis, therefore, three generic levels of information determined by the loop closure hypotheses and consistent with cost considerations can be identified which served to form the basis of the electronic display formats that comprised the major display variable in the Reference 2 experiment:

- ED-1: orientation, position, and commanded position
- ED-2: orientation, position, commanded position, velocity and commanded velocity information
- ED-3: orientation, position, commanded position, and velocity, with longitudinal (δ_{es}), lateral (δ_{as}), and thrust magnitude (δ_{cs}) control director information.

A general consideration that resulted from the experiment design philosophy, just discussed, on which these formats were based is that these

three levels of information were consistent within themselves: if one translational velocity was assumed available, all three velocity components were assumed available, for example. Additionally, command information was consistent with status data and followed the same general hierarchy (position commands ⟹ velocity commands ⟹ control commands): the intent was to provide explicitly to the pilot all the information for each set of loop closures. Clearly, by relaxing the constraint on consistency, a plethora of possible combinations could be examined to focus on specific axes or aspects of the pilot's control problem, and, in fact, one such "mixed" format was included to concentrate on vertical tracking difficulties (ED2+). In general, however, by concentrating on consistent generic levels of information, the fundamental aspects of the control-display interaction were felt more likely to be highlighted.

The intent of the design of the electronic display formats in the Reference 2 experiment was to present the information to the pilot in as favorable a manner as possible in order to concentrate on differences in levels of information. Accordingly, previous work of Dukes (Reference 25) and Young (26) in the formulation of principles for integrated display design was used as a basis for the designs, in conjunction with the experimental results from Dukes (Reference 27) and the RAE CL-84 investigation (Reference 14). The basic guidelines used are also directly applicable to the development of HUD formats for the current experiment, and are:

- Aircraft-referenced display - The aircraft symbol position is fixed and the other displayed information moves with respect to this reference.

- Error display - The guidance information is presented in the form of errors rather than as absolute values where possible.

- Explicit display of rates - No attempt is made to have the pilot estimate absolute or error rates implicitly by the rate of change of a position symbol on the display. When rates are displayed, they are displayed explicitly.

- Display of lead information - When rate information is displayed, its function is to lead the position symbol to aid the pilot in his prediction of a future aircraft state.

- Symbol response to control input - The location of a symbol and the sense of its motion are selected to be compatible with the location and motion of its primary controller.

- Scaling of the displayed parameters - The scaling of the various symbol motions is selected so as to be acceptable to the pilot while not significantly degrading overall system performance. A relatively simple display with fast-moving symbols may appear "cluttered" to the pilot while a more complex display with slow-moving symbols may be acceptable to him but may also result in a relatively poor total system performance.

The formats designed on these bases are repeated from Reference 2 in Figure 6-1 for comparison with the formats investigated in this experiment. Note that no digital readout (alphanumeric) information was presented, because the symbol generator used in that experiment did not have this capability. As was reviewed in Section 2 of this report, the position-data-only format (ED-1) was found unacceptable for the full instrument deceleration regardless of control augmentation. The information contents of formats ED-2 and ED-3 were therefore used as the basis for AV-8B HUD format modifications in the current experiment, and were also modified to be presented head-up themselves.

6.3 BASIC AV-8B HUD FORMAT

The HUD format proposed for the AV-8B at the start of this contract was developed by McDonnell-Douglas (MCAIR) as a modification to the AV-8A operational HUD. The series of simulations during which the modifications were made culminated in the Reference 10 simulation, and it is the format from that study which was used as the "basic" AV-8B HUD in this X-22A experiment.

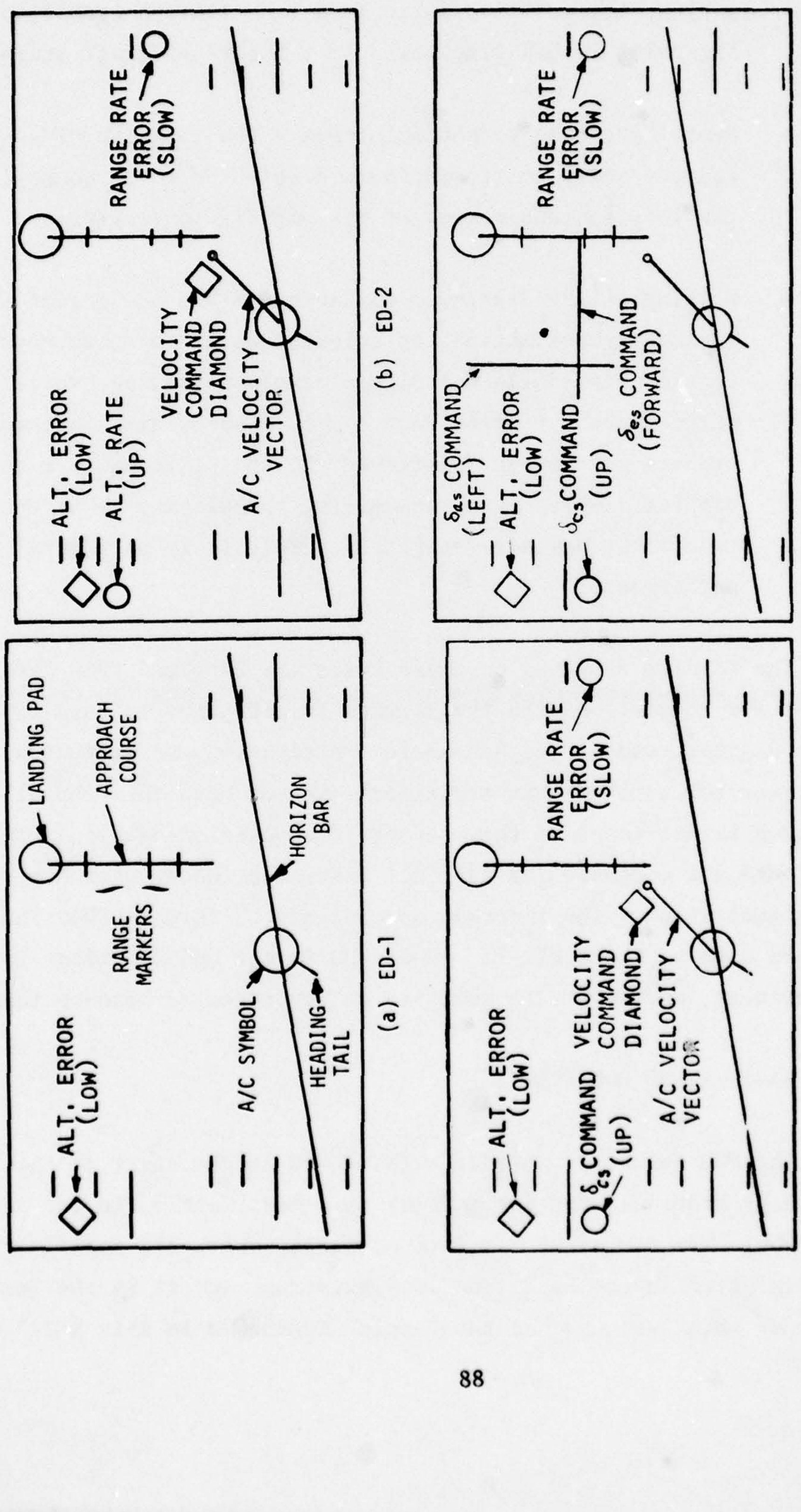


Figure 6-1 REFERENCE 2 DISPLAY FORMATS

This format is shown in Figure 6-2, and will be designated "AV8-Ø" throughout this report.

The MCAIR format has the following differences from the operational AV-8A display:

1. Pitch ladder scaling at 3:1 vice 5:1 in the AV-8A.
2. Two-axis flight director vice none in the AV-8A.
3. Guidance source marker vice none in the AV-8A.
4. Digital range-to-touchdown vice none in the AV-8A.

With regard to the information levels reviewed in the previous subsection, the data presentation on this format has the characteristics outlined below.

- Orientation and Position Information

  Orientation data is presented via an attitude ladder and a heading tape. The roll scaling is 1:1, while the pitch scaling is 3:1. The ladder "rungs" are broken in the middle so that they don't pass through the aircraft symbol. According to Reference 10, the 3:1 scaling was considered preferable to the 5:1 scaling of the AV-8A and to 1:1 scaling as used in CTOL aircraft. Reference 14 notes that in the CL-84 HUD program, scalings of 5:1 and 2:1 elicited varying pilot comments, and no specific conclusion was drawn. Position data are provided in an analog fashion laterally (localizer) and vertically (glideslope) by the position of the guidance source marker relative to the fixed aircraft symbol in the center of the display plus a digital altitude readout, and longitudinally (range) via a digital readout.

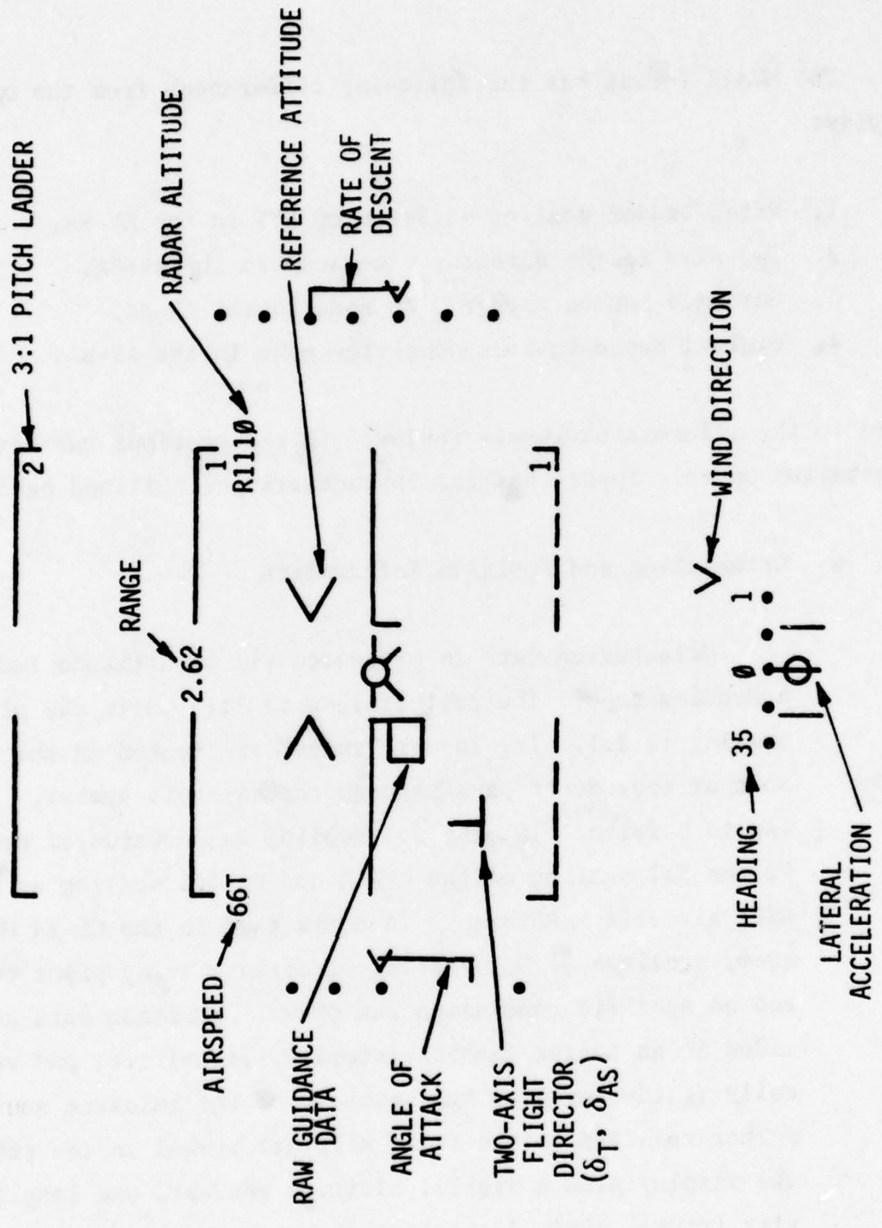


Figure 6-2 PROPOSED AV-8B HUD FORMAT (AV8-Ø)

- Velocity Information

  Vertical velocity data is presented in analog fashion by a rate-of-climb "thermometer" on the right of the display, and longitudinal velocity (airspeed) via a digital readout. No data concerning longitudinal or lateral groundspeed are presented. Additional air-sensed velocity data are given by an angle-of-attack thermometer and a sideslip (lateral acceleration) ball. No command or error velocity data are shown.

- Control Director Information

  Control directors for throttle and lateral stick are given in analog fashion by the position of a single symbol relative to the fixed aircraft signal. No longitudinal stick director information is provided. No explicit deceleration command such as the ITVIC used in Reference 2 is provided.

Based on the previous X-22A results and the analyses of other displays presented in Reference 2, it was hypothesized that the characteristics of the AV8-Ø format just summarized might be deficient in the following items:

1. Central location of glideslope information. For VTOL aircraft in terminal area deceleration, rate of climb and hence vertical position is generally controlled by thrust magnitude. It was found in the CL-84 program (Reference 14) that the central location used for glideslope brackets created problems in glideslope tracking because of a tendency to chase them with pitch attitude.

2. Rate-of-climb information on right side of display. Since rate-of-climb is controlled with the throttle, which is a left-hand operation, the location of this information on the other side of the display (which is based on CTOL practice) is inconsistent.

3. Separated glideslope error and rate-of-climb information. Vertical tracking is generally a difficult task for VTOL aircraft because of their low inherent vertical velocity damping. For this reason, rate-of-climb information — preferably as an error from that desired — can supply necessary lead information if displayed near the glideslope error symbol.

4. Digital airspeed readout. Although appropriate for constant speed velocity tracking, it is possible that analog velocity status data as presented in References 2, 14, and 26 is required during deceleration. Similarly, velocity command information was found desirable in Reference 2.

5. Lack of lateral ground velocity data. Localizer tracking for VTOL aircraft becomes more difficult as speed decreases because a given bank angle results in larger turn rates. Ground-referenced lateral velocity information provides useful lead information for this problem.

6. Lack of deceleration command. The deceleration portion of the task was found very difficult with the CL-84 (Reference 14), and in the previous X-22A experiment a separate command, called ITVIC, was developed to provide display information for this aspect of the task. In addition, logic was developed to initiate the deceleration at ranges dependent on headwind. Although the AV-8B deceleration task is considerably simpler, having this command explicitly would permit similar logic to be used.

7. Lack of longitudinal stick director. Poor attitude flying qualities can be alleviated to some extent by providing the pilot with a longitudinal stick control director that assists him in stabilizing the aircraft. Previcus research of decelerating instrument approaches has included such directors (e.g. References 2, 3, 8, 12).

8. Throttle and lateral stick directors on one symbol. Since the throttle and stick are separate controllers operated by separate hands, the single symbol is inconsistent with the principles summarized in the preceding subsection.

These hypothesized deficiencies of the AV8-Ø format for instrument decelerations to hover provided the rationale for a series of modified formats that were designed for investigation in the experiment. These formats are described in the following subsection.

6.4 AV EXPERIMENT FORMATS

Figure 6-3, a through f, presents the experiment formats. Descriptions of the modifications to the basic AV8-Ø format in terms of the hypothesized deficiencies being examined are given below.

6.4.1 AV8-Ø

The only change to the basic format was the incorporation of the deceleration initiation command logic described in Section 5 to flash the airplane symbol as a command to move the nozzles to the hover stop. All formats included this command on the basis of Item 6 discussed previously. In addition, a wind direction chevron, which is driven by differences between air-sensed and MLS-derived velocities, was added as a result of a recommended improvement in Reference 2; the chevron is scaled the same as the heading tape, and was also included on all formats. The remainder of the format was unchanged.

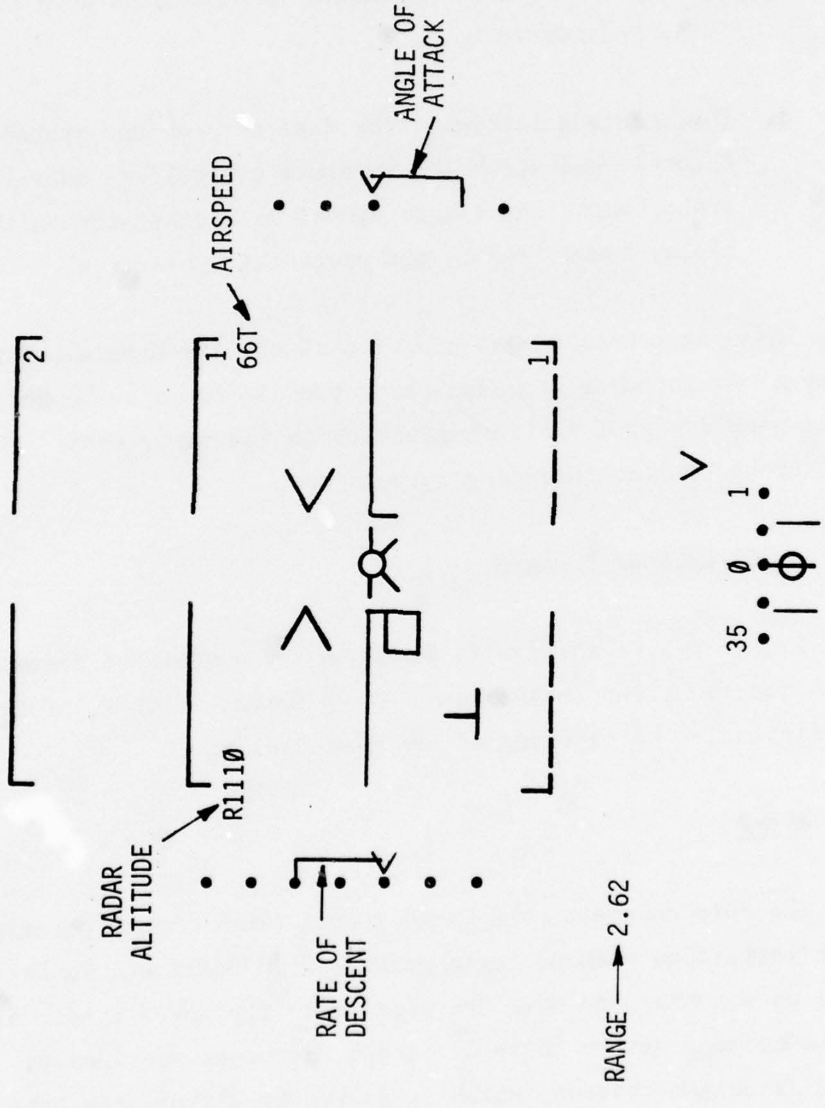


Figure 6-3a AV8-1 FORMAT

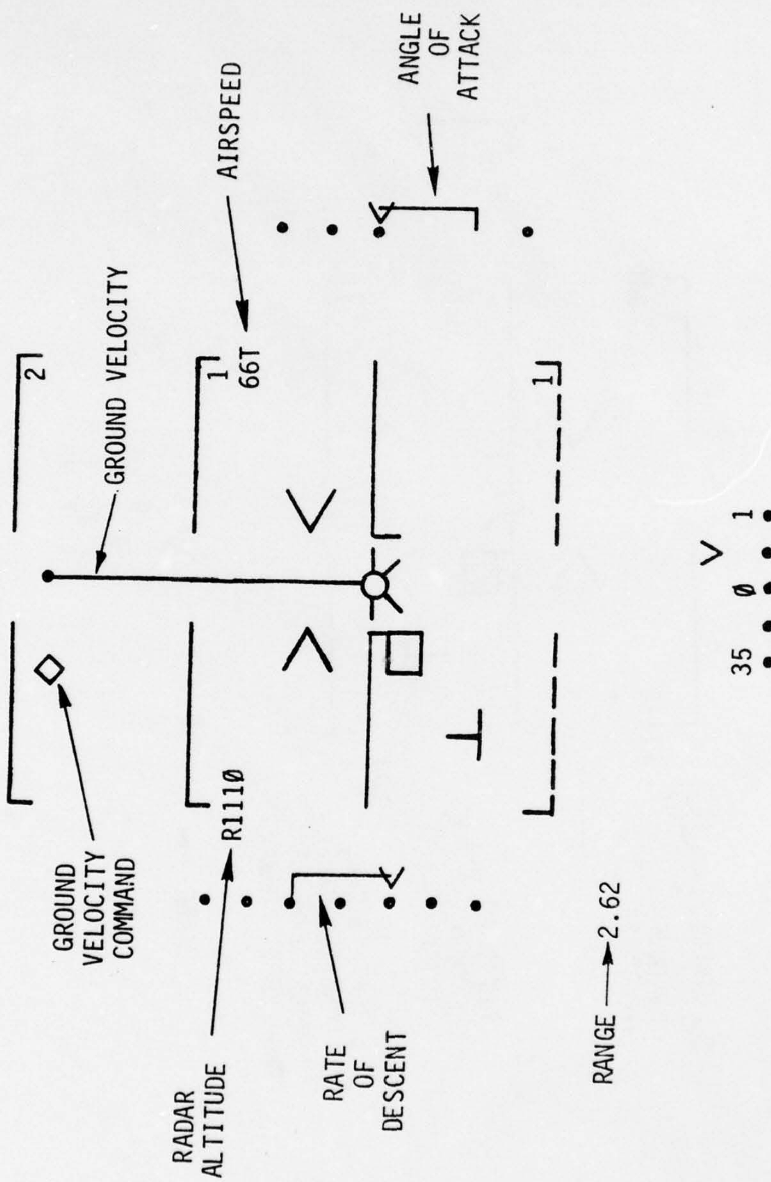


Figure 6-3b AV8-2 FORMAT

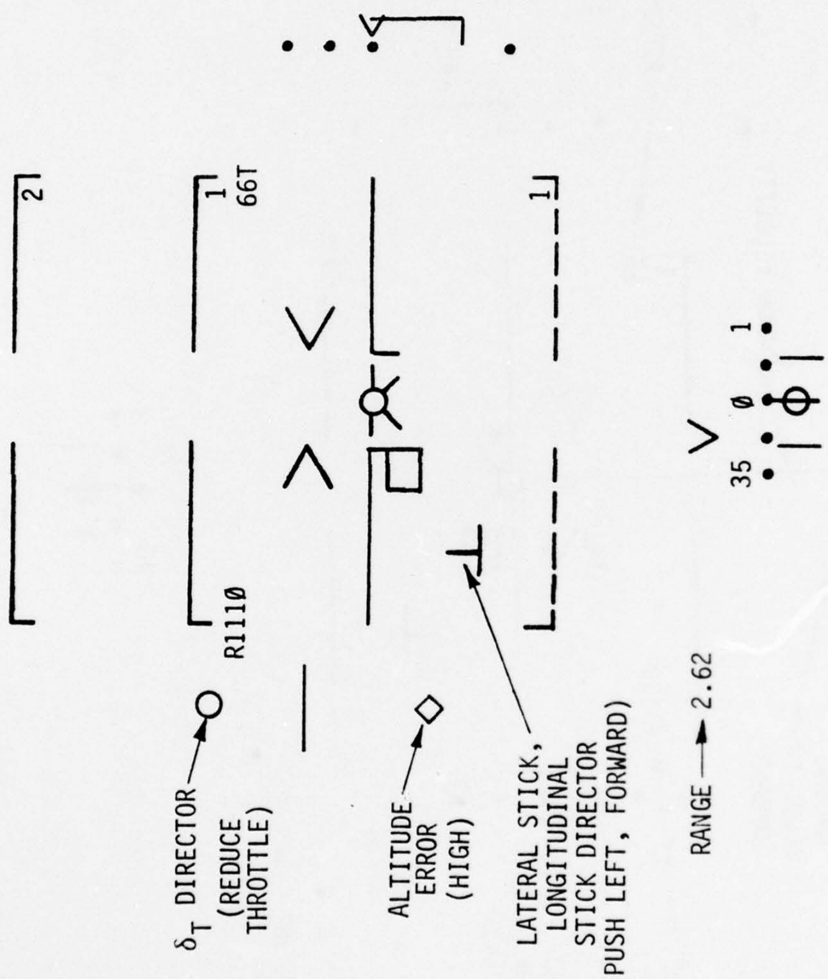


Figure 6-3c AV8-3 FORMAT

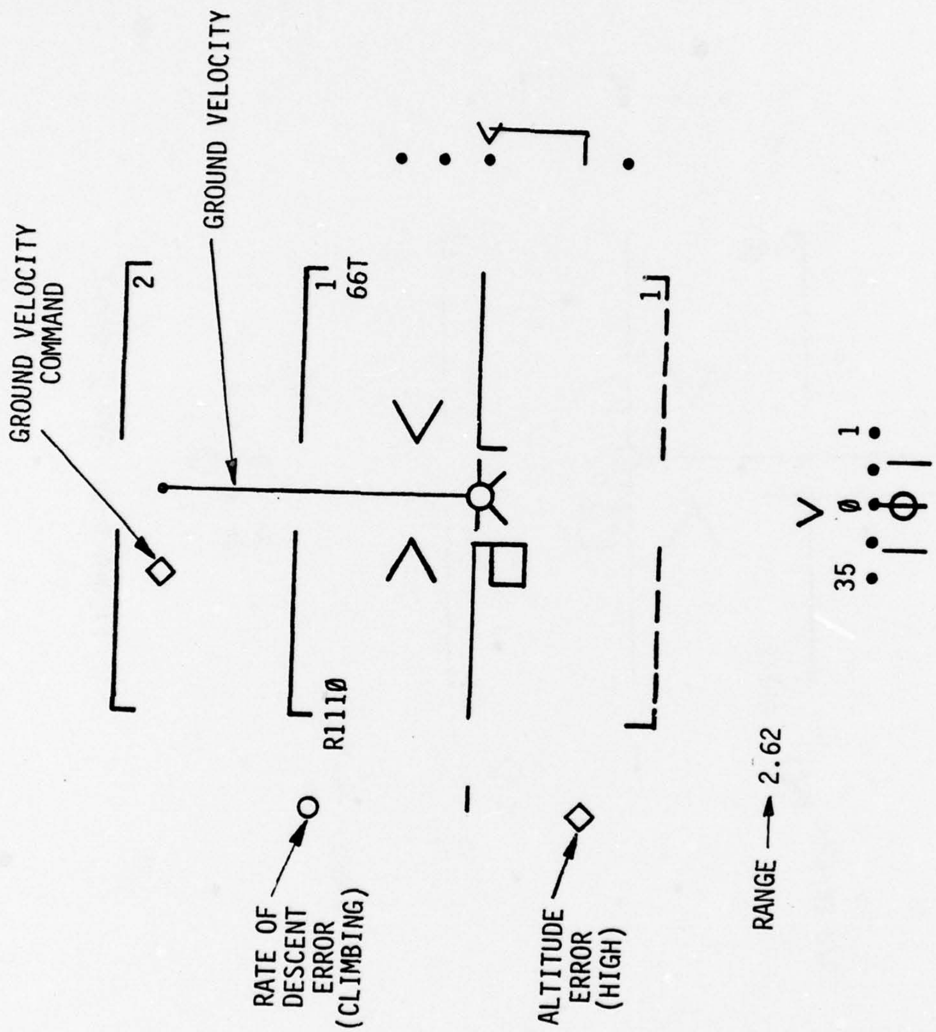


Figure 6-3d AV8-4 FORMAT

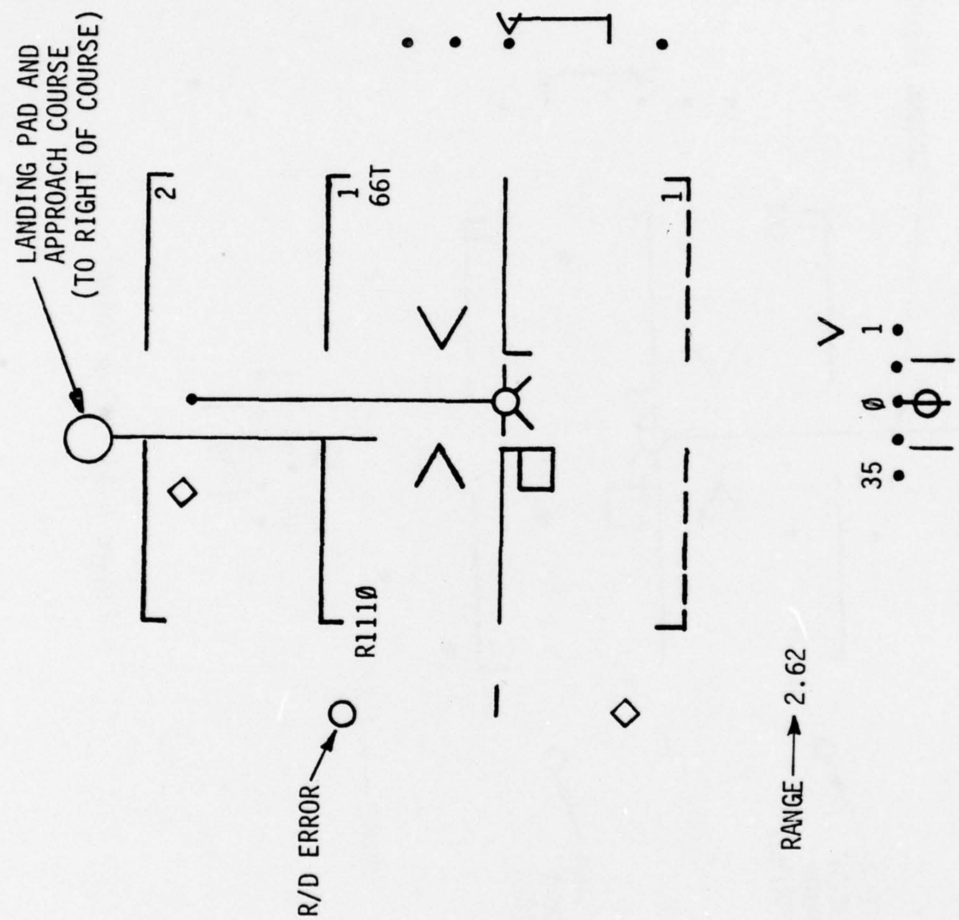


Figure 6-3e AV8-5 FORMAT

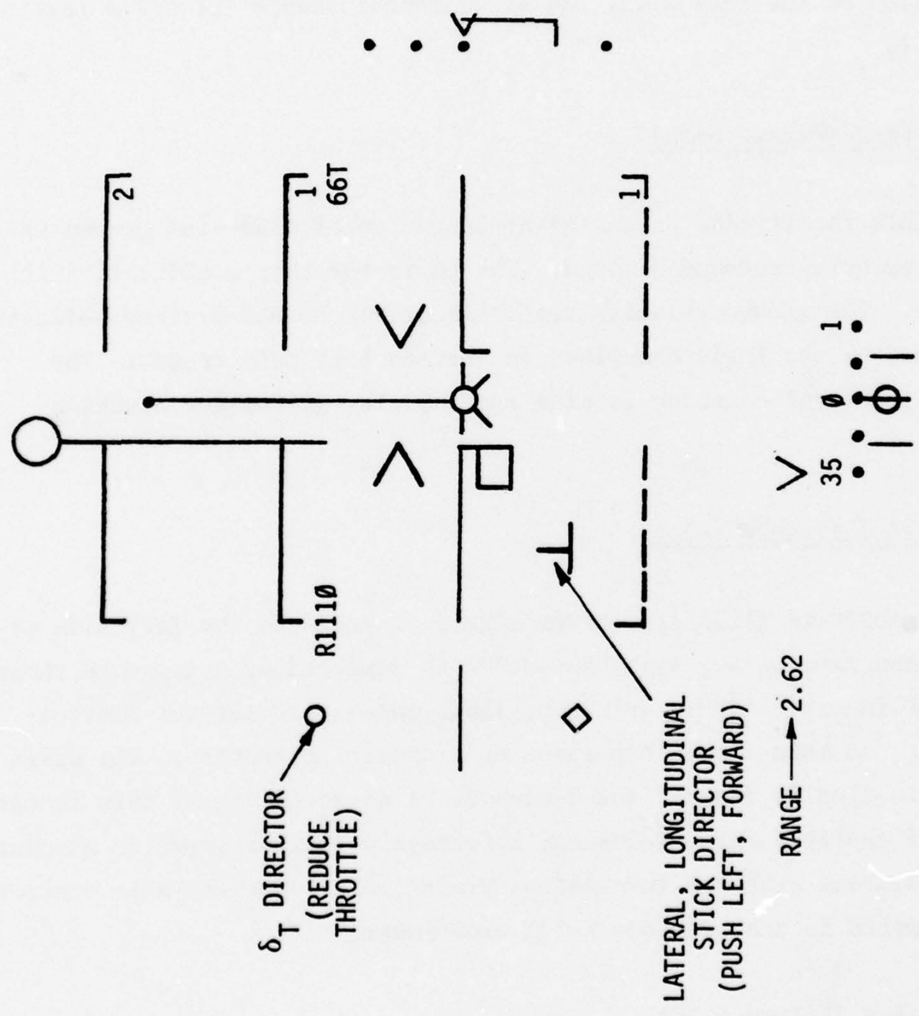


Figure 6-3f AV8-6 FORMAT

6.4.2 AV8-1 (Figure 6-3a)

This format transposes the rate-of-climb/altitude readout and angle-of-attack/airspeed readout on the basis of Item 2. The vertical status information is on the left-hand side of the display to correspond to left-hand throttle control. The remaining formats (AV8-2 through AV8-6) all have this information on the left also. No other format changes to AV8-Ø were made for AV8-1.

6.4.3 AV8-2 (Figure 6-3b)

This format adds an analog presentation of plan-view ground velocity plus a velocity command diamond. The basis for this modification is Items 4 and 5. The ground velocity vector is driven by MLS-derived velocities, and the command by the logic described in Section 5 of this report. The AV8-Ø two-axis control director is also retained for glideslope tracking assistance.

6.4.4 AV8-3 (Figure 6-3c)

A separate glideslope error signal is added to the left side of the display, and rate-of-descent information is replaced by a separate throttle director. The inverted "T" is driven by longitudinal and lateral control-director logic, so this format has three axis control directors. The basis for the modification is Items 7 and 8 plus 3. A disadvantage of this format is the lack of explicit rate-of-descent information (either error or absolute), but it is consistent with the information presentation of three-axes control directors examined in the previous X-22A experiment.

6.4.5 AV8-4 (Figure 6-3d)

This format is an alternate modification to AV8-2. The two-axis control director is removed, and rate-of-descent is replaced by rate-of-descent error and glideslope error on the left side. The sense and scaling of the

vertical error symbols is such that moving the circle to the diamond assures glideslope capture and tracking, yet the actual error data is presented. The basis for the modification is Items 1, 2, 3, 4 and 5.

6.4.6 AV8-5 (Figure 6-3e)

To the AV8-4 format are added plan view localizer and range information in analog form. The basis is again Items 1 through 5. An additional intent was to present all of the velocity and position data in the same fashion as was done in Reference 2 and the ED2-Ø format to be discussed in the next subsection, thereby focussing on differences in attitude information presentation (pitch scaling, ladder versus horizon,broken versus solid lines).

6.4.7 AV8-6 (Figure 6-3f)

This format adds three-axis control directors to AV8-5; alternately, it may be viewed as adding analog plan view velocity and position information to AV8-3. The basis is Items 1-5, 7, and 8; the information content is also equivalent to format ED2-2 to be discussed.

As will be discussed in Section 8 of this report, flight hour and schedule constraints precluded the flight evaluation of formats AV8-1, AV8-2, and AV8-4, although a brief examination of them was performed on the X-22A ground simulator. Some of the individual effects of Items 2 and 5 were therefore not examined independently. The scaling of the information to the symbols on all the AV formats is given in Table 6-1; in general, the scalings were selected to be the same as the AV8-Ø format or the symbol scaling from Reference 2. One mistake was made, however. The inverted "T" control director is constrained in the MCAIR format to within a 5° (pilot's field of view) circle around the aircraft symbol; this movement is considerably larger than the control director motions permitted in the previous X-22A experiment, but the full scale sensitivities used (centimeters/volt) were mistakenly made the same. The influence of this difference will be discussed with regard to the pilot rating results in Section 8 of this report; the control director logic used

TABLE 6-1
AV FORMAT SCALINGS

SIGNAL	ANALOG SCALE	AV-8B SYMBOL	DISPLAY* SCALE	REMARKS
α	$.4\ \alpha$ 10V=25°	Vectored Chevron	0.49°/V	Scale Dots at -5, +8, +12, +16 deg(α)
n_y	20 n_y 10V=.5 g	Circle	0.20°/V	Scale Lines at -.3, 0, +.3 g
$\hat{\dot{z}}$	.1 $\hat{\dot{z}}$ 10V=100 Ft/Sec	Vectored Chevron	0.95°/V	Scale Dots at +1000, +500, -500, -1000, -1500, -2000 FPM
$\hat{z}_e$	.004 $\hat{z}_e$ 10V=2500 Ft	Digital Readout		5 Ft Increments
$\hat{x}$	.000333 $\hat{x}$ 10V=30,000 Ft	Digital Readout		.01 Nautical Mi. Increments
u	.032 u 10V=313 Ft/Sec	Digital Readout Tape		1 Knot/Inc. Dig. = 10 Kts, Dot = 5 Kts
θ	10 sin θ 10V=90°	Pitch Ladder	1.94°/V	AV Lines at 10° intervals alt. lines at 5° intervals
ϕ	10 sin ϕ 10V=90°	Pitch Ladder		Rotation 1 to 1
ψ	10 sin ψ 10 cos ψ 10V=90° 4 Quad=360°	Heading Tape	0.20°/V 1.25°/V	Numerals every 10° ψ Dot every 5° ψ
V_{BAR}	±5V F.S.	Inverted T	0.98°/V	
V_{TAB}	±5V F.S.	Inverted T Circle	0.98°/V 0.46°/V	
LOC	±5V F.S.	Square	0.98°/V	
G.S.	±5V F.S.	Square	0.98°/V	
$\hat{\dot{x}}$	.025 $\hat{\dot{x}}$ 10V=400 Ft/Sec	Vectored Circle	2.08°/V 8.30°/V	Approach Hover Mode
$\hat{\dot{y}}$	.05 $\hat{\dot{y}}$ 10V=200 Ft/Sec	Vectored Circle	1.04°/V 4.15°/V	Approach Hover Mode
$\dot{x}_c$	.04 $\dot{x}_c$ 10V=250 Ft/Sec	Diamond	1.30°/V 5.20°/V	Approach Hover Mode
$\dot{y}_c$	.05 $\dot{y}_c$ 10V=200 Ft/Sec	Diamond	1.15°/V 4.62°/V	Approach Hover Mode
H_{BAR}	±5V F.S.	Inverted T	0.98°/V	
ϵ_z	.1 ϵ_z 10V=100 Ft	Diamond	.464°/V	
$\hat{x} \cdot f(x)$	.0005 $\hat{x} \cdot f(x)$ See Fig. I-1	Circle	1.22°/V	Landing Pad x Displacement
$\hat{y} \cdot f(x)$	-.002 $\hat{y} \cdot f(x)$ See Fig. I-1	Circle	0.21°/V	Landing Pad y Displacement
$f(h)$	See Fig. I-2	Circle	0.52°/V	Landing Pad Size
$H_{REF}/EARTH_{REF}$	Switch 0/5 V			
HOVER MODE	Switch 0/10 V			Change Scale of Vel. Vec. & Vel. Ind. X 4
ITVIC	Switch 0/6 V			Flash A/C Symbol
$V_{WIND\ X}$	.2 V_{WX} 10V=50 Ft/Sec	Chevron		
$V_{WIND\ Y}$	.2 V_{WY} 10V=50 Ft/Sec	Chevron		

*Angle subtended at pilot's eye by HUD symbol or symbol displacement

for both the AV and ED formats in this experiment is discussed in Section 6.6.

6.5 ED EXPERIMENT FORMATS

To focus on attitude presentation specifically, an alternate group of formats based on head-up presentation of the Reference 2 head-down displays was designed for investigation. These formats, designated ED2-Ø, ED2-1, and ED2-2, correspond essentially to formats ED-2, ED-2+, and ED-3 of Figure 6-1; the head-up versions are shown in Figure 6-4, a-c. For this case, the head-down pitch attitude scaling, based on a 3-inch ADI, is maintained for the head-up presentation (approximately 16:1). A larger airplane symbol is used, so that ± 5 degrees pitch attitude corresponds to the bottom and top of the airplane symbol. By virtue of the reduced sensitivity, only a horizon bar is used rather than a ladder; it may therefore be solid, rather than broken to avoid intersecting the aircraft symbol, because of the reduced display clutter. The following modifications to the head-down formats were made for this experiment.

- Improved roll attitude display through a roll index at the top plus "wings" on the aircraft symbol.

- Display of angle of attack (and limits) to correspond to this data on the AV formats.

- Display of lateral acceleration and limits to correspond to the AV formats.

- The wind chevron as per the AV formats.

- Digital readouts of altitude, range, and airspeed plus tape readout of heading as per the AV formats.

The information content of ED2-Ø corresponds to AV8-5, and ED2-2 corresponds to AV8-6; format ED2-1 has a single control director (throttle).

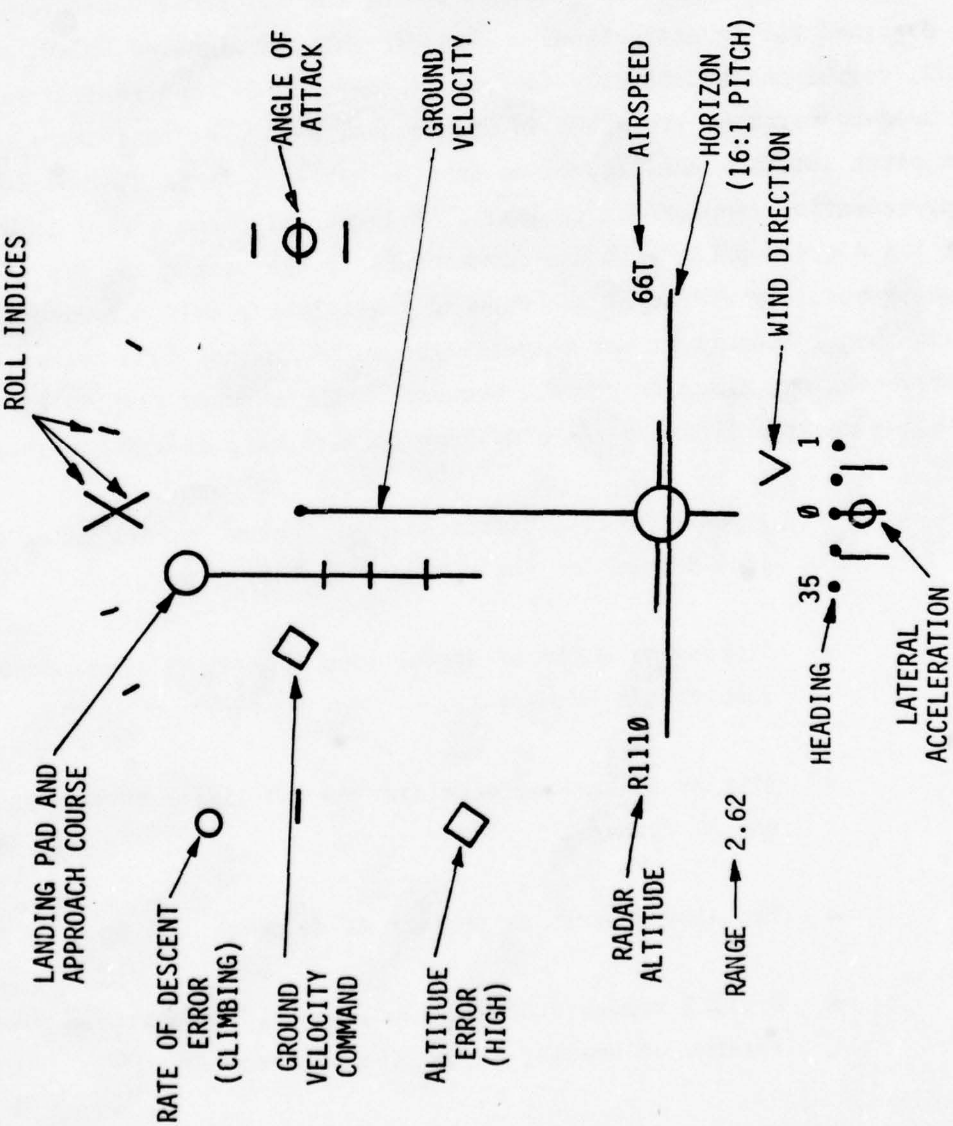


Figure 6-4a ED2-Ø FORMAT

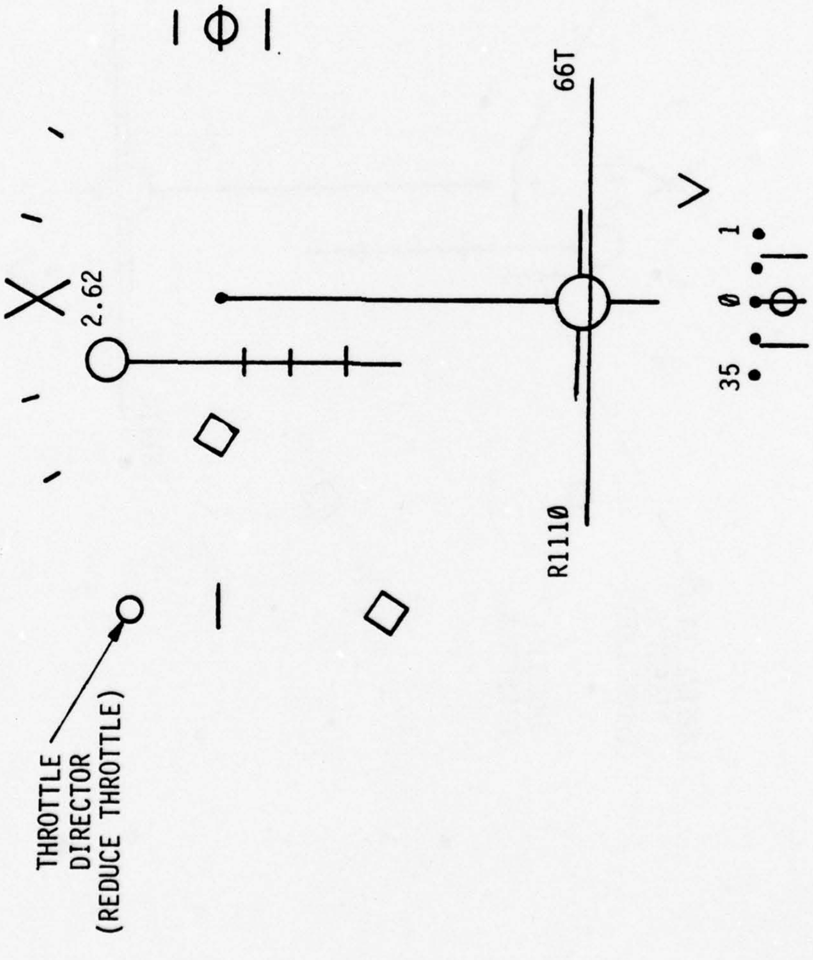


Figure 6-4b ED2-1 FORMAT

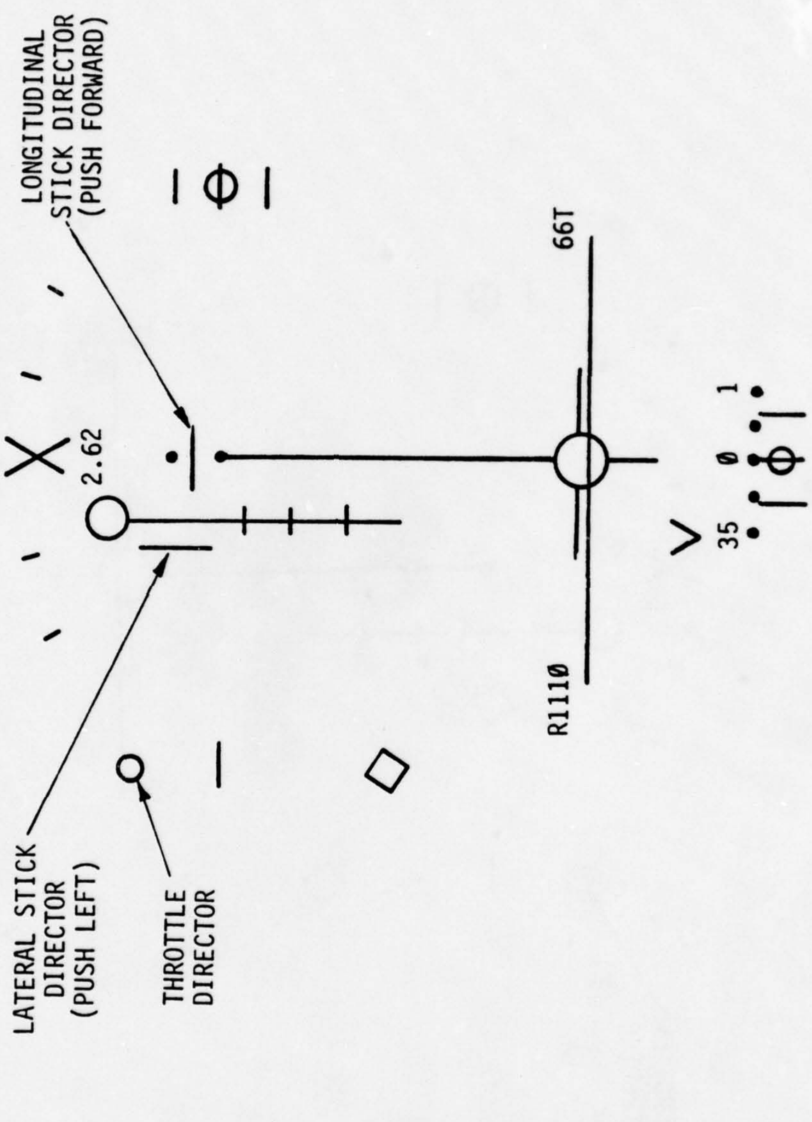


Figure 6-4c ED2-2 FORMAT

The scalings for these formats are given in Table 6-2. A summary of the information content of all the AV and ED formats is given in Table 6-3.

6.6 CONTROL DIRECTOR LOGIC

The design of the logic driving the control directors in this experiment used the same philosophy as in the previous X-22A experiment; Section VI of Reference 2 contains a detailed discussion of why this philosophy was adopted. Basic principles which were retained for this experiment are:

- Design condition - the precision hover was the design condition for the control director.
- Simplified logic - an attempt was made to minimize the need for logic switching, error limiting, and gain scheduling.
- Use of manual control theory - the response of the director elements to control inputs must be acceptable to the pilot and yet not significantly degrade overall system performance. In particular, the design is predicated upon attempting to achieve a wide frequency range of K/S response to control inputs; this requirement leads to different control director gains for different controlled element characteristics (aircraft response dynamics).
- Separate directors - each director commands one controller input directly. Hence, if rudder is excluded, directors for longitudinal stick, lateral stick, throttle, and nozzle angle are, in general, required.

The designs of each director are summarized in the following subsections. Only the directors which were actually evaluated in flight are presented; the characteristics are based upon the computed AV-8B simulation characteristics presented in Section 3.

TABLE 6-2
ED FORMAT SCALINGS

SIGNAL	ANALOG SCALE	ED SYMBOL	DISPLAY* SCALE	REMARKS
α	$.4\ \alpha$ 10V=25°	Circle	0.51°/V	Scale Lines at 0, 6, 12 deg (α)
n_y	$20\ n_y$ 10V=.5 g	Circle	0.20°/V	Scale Line at -.3, 0, +.3 g
$\hat{z}$	$.1\ \hat{z}$ 10V=100 Ft/Sec			
$\hat{z}_e$	$.004\ \hat{z}_e$ 10V=2500 Ft	Digital Readout		5 Ft Increments
$\hat{x}$	$.000333\ \hat{x}$ 10V=30,000 Ft	Digital Readout		.01 Nautical Mi Increment
u	$.032\ u$ 10V=313 Ft/Sec	Digital Readout Tape		1 Knot/Inc. Dig. = 10 Kts, Dot = 5 Kts
θ	$10 \sin \theta$ 10V=90°	Horizontal Line	0.36°/V	At 10° (1.7 V) Horiz. Line Tangent to A/C Symbol
ϕ	$10 \sin \phi$ 10V=90°	Horizontal Line & Roll Chevron and Scale		Rotation 1 to 1
ψ	$10 \sin \psi$ $10 \cos \psi$ 10V=90° 4 QUAD = 360°	Heading Tape	0.20°/V 1.25°/V	Numerals every 10° ψ Dot every 5° ψ
V_{BAR}	±5V F.S.	Cross Pointer Line	0.24°/V	
V_{TAB}	±5V F.S.	Circle	0.46°/V	
LOC	±5V.F.S.			Not Used
G.S.	±5V F.S.			" "
$\hat{\dot{x}}$	$.025\ \hat{\dot{x}}$ 10V=400 Ft/Sec	Vectored Circle	2.08°/V 8.30°/V	Approach Hover Mode
$\hat{\dot{y}}$	$.05\ \hat{\dot{y}}$ 10V=200 Ft/Sec	Vectored Circle	1.04°/V 4.15°/V	Approach Hover Mode
$\dot{x}_c$	$.04\ \dot{x}_c$ 10V=250 Ft/Sec	Diamond	1.30°/V 5.20°/V	Approach Hover Mode
$\dot{y}_c$	$.05\ \dot{y}_c$ 10V=200 Ft/Sec	Diamond	1.15°/V 4.62°/V	Approach Hover Mode
H_{BAR}	±5V F.S.	Cross Pointer Line	0.24°/V	
ϵ_z	$.1\ \epsilon_z$ 10V=100 Ft	Diamond	0.24°/V	
$\hat{x} \cdot f(x)$	$.0005\ \hat{x} \cdot f(x)$ See Fig.I-1	Circle	1.22°/V	Landing Pad x Displacement
$\hat{y} \cdot f(x)$	$-.002\ \hat{y} \cdot f(x)$ See Fig.I-1	Circle	0.21°/V	Landing Pad y Displacement
$f(h)$	See Fig.I-2	Circle	0.52°/V	Landing Pad Size
$H_{REF}/EARTH_{REF}$	Switch 0/5 V			Rotate A/C Tail or Approach Path (ψ)
HOVER MODE	Switch 0/10 V			Change Scale of Vel. Vec. & Vel. Inc. X 4
ITVIC	Switch 0/6 V			Flash A/C Symbol
$V_{WIND\ X}$	$.2\ V_{\omega x}$ 10V=50 Ft/Sec	Chevron		
$V_{WIND\ Y}$	$.2\ V_{\omega Y}$ 10V=50 Ft/Sec	Chevron		

*Angle subtended at pilot's eye by HUD symbol or symbol displacement

TABLE 6-3

DISPLAY INFORMATION CONTENTS

AV-8/ED FORMAT	ORIENTATION	POSITION		RATE		DIRECTOR
		VERTICAL	HORIZONTAL	VERTICAL	HORIZONTAL	
AV8-ϕ, AV8-1	BASIC PITCH LADDER; HEADING TAPE; ANGLE OF ATTACK	ILS BOX AND ALTITUDE READOUT	ILS BOX AND RANGE	$\dot{h}$ DISPLAY	V (DISCRETE) READOUT	2-AXIS
AV8-2	SAME AS ABOVE + ALT. PITCH DISPLAY	BOX AND ALTITUDE READOUT	BOX AND RANGE	$\dot{h}$	V (DISCRETE/TAPE) VELOCITY VECTOR	2-AXIS
AV8-3	SAME AS ABOVE	BOX AND ALTITUDE; ALT. ERROR DIAMOND	BOX AND RANGE	VTAB DIRECTOR	V (DISCRETE/TAPE)	3-AXIS
AV8-4	SAME AS ABOVE	BOX AND ALTITUDE; ALT. ERROR DIAMOND	BOX AND RANGE	ALT. RATE ERROR	V (DISCRETE/TAPE) VELOCITY VECTOR	NONE
AV8-5	SAME AS ABOVE	ALTITUDE READOUT; ALT. ERROR DIAMOND	RANGE + LANDING PAD	SAME AS ABOVE	SAME AS ABOVE	NONE
AV8-6	SAME AS ABOVE	SAME AS ABOVE	SAME AS ABOVE	VTAB DIRECTOR	SAME AS ABOVE	3-AXIS
ED2-ϕ, ED2-1	ATTITUDE DISPLAY; HEADING TAPE; ANGLE OF ATTACK + LIMITS; HEADING TAIL; OPT. ROLL DISPLAY	ALTITUDE READOUT; ALT. ERROR DIAMOND	RANGE READOUT; LANDING PAD	ALTITUDE RATE ERROR	VELOCITY VECTOR; V (DISCRETE/TAPE)	NONE
ED2-1	SAME AS ABOVE	SAME AS ABOVE	SAME AS ABOVE	VTAB DIRECTOR	SAME AS ABOVE	1-AXIS
ED2-2	SAME AS ABOVE	SAME AS ABOVE	SAME AS ABOVE	VTAB DIRECTOR	SAME AS ABOVE	3-AXIS

6.6.1 Longitudinal Stick Control Director Logic

The longitudinal stick control director design is based on the assumption of "backside" operation: that is, pitch attitude is the primary airspeed control. For the AV-8B after the nozzle change, this assumption is valid because of the vertical thrust inclination; although the aircraft is slightly "frontside" at 65 kt, the high thrust inclination simulated ($\theta_f = 70^{\circ}$) implies that throttle inputs are primarily a rate-of-climb controller and that the "backside" philosophy is still appropriate. During the transition, the coarse speed control is determined by the nozzle change and effective drag damping of the aircraft. The function of the longitudinal stick director, therefore, is to provide a vernier control to assist in maintaining correct angle of attack and to assist the pilot in performing pitch attitude stabilization.

The equation that results from these considerations for the longitudinal control director is:

$$\text{HBAR} = K_{\dot{x}}\, \epsilon_{\dot{x}_h} + K_{\theta}\, \theta_{wo} + K_q q = K_{\dot{x}} (\dot{x}_{h_c} - \hat{\dot{x}}_h) + K_{\theta}\, \theta_{wo} + K_q q$$

The $K_{\dot{x}}$ gain is selected on a priori bases. In the previous experiment, a value of .150 volts/ft/sec (± 5 volts full scale) was used on the basis of ground simulation, yielding a maximum deflection for 33 ft/sec velocity error (Reference 2). This same value was used in the current experiment because of the intention to examine a 105 kt initial approach speed. It is possible that a more sensitive scaling (e.g., maximum deflection for 20 ft/sec) could have been used for the 65 kt approach, but the previous experiment indicated that the sensitivity in hover was reasonable with 33 ft/sec full scale, and so this value was retained.

The remaining two gains (K_{θ} and K_q) were used to attempt to achieve over a wide frequency band a K/s -like response of the director to longitudinal stick inputs. These gains therefore depend on the control system implemented, and are generally different for each one; the gains did not, however,

vary with flight condition. Initial estimation of these gains was based on approximate hover transfer functions as summarized in Reference 2; the director responses, with these gains, were then checked using the exact transfer functions. Table 6-4 summarizes K_θ and K_q for the control systems evaluated in conjunction with a flight director display format that included the longitudinal stick director:

TABLE 6-4

HBAR GAINS (K_θ, K_q)

Control System	K_θ (volt/rad)	K_q (volt/rad/sec)	Flight Number
AVSAS	4.93	.69	164, 165, 166
	4.93	1.40	178, 179, 181
2.0 RCAH	4.01	1.06	169
1.0 ACAH	10.77	2.29	164, 165, 166
	10.57	4.79	180
1.5 ACAH	7.94	2.91	179

It will be noted that two sets of K_q gains were investigated for the AVSAS and 1.0 ACAH control systems. When the airplane is not highly augmented, the design procedure results in high sensitivity to q in the control director to obtain the desired response (K_q = .69 for AVSAS, K_q = 2.29 for 1.0 ACAH). The pilot comments with these gains (Appendix II) indicated noisy director signals, however, and so the sensitivites were reduced by approximately one-half for later flights. As the hover Bode plots given in Appendix I show, these changes actually made a small improvement in the phase characteristics at higher frequencies, but essentially the overall gain/phase characteristics are similar. Appendix I summarizes the HBAR/δ_{ES} transfer functions.

6.6.2 Throttle Control Director Logic

Based on the "backside" control philosophy, the purpose of the throttle director is to provide assistance in glide slope and rate-of-descent

tracking. The equation that results is therefore:

$$VTAB = K_z \epsilon_z + K_{\dot{z}} \epsilon_{\dot{z}}$$

Considering the decoupled hover approximation, this equation becomes:

$$\frac{VTAB}{\delta_T} = \frac{K_{\dot{z}} Z_{\delta_T} (s + K_z/K_{\dot{z}})}{s(s - Z_w)}$$

On this basis, it can be seen that if the ratio $K_z/K_{\dot{z}}$ can be set equal to $-Z_w$, the director will look like a pure K/S over all frequencies. The difficulty for VTOL machines is that Z_w is small in hover for high disk loading or jet-lift machines and that its magnitude varies extensively with flight condition; these characteristics imply probable sensitivity problems in hover and, further, that a director optimized for hover may be too sensitive for up-and-away flight. For this reason, one of the gains (K_z or $K_{\dot{z}}$) needs to be variable with flight condition; $K_{\dot{z}}$ is the correct choice since the overall director gain can then also vary.

Using $Z_w \cong -.02$ in hover for the AV-8B, and a value of K_z that gives full scale deflection of 100 ft. as in Reference 2 (e.g. K_z = 5 volts/100 ft = .05 v/ft), the design procedure would give a hover value for $K_{\dot{z}}$ of 2.5 volts/ft/sec, yielding full scale deflection for only 2 ft/sec error. This value was found to be too sensitive in preliminary ground simulations, as might be expected. On the ground simulator, the same hover gains used in the Reference 2 experiment (K_z = .05, $K_{\dot{z}}$ = .5, ratio = .1) were found to be suitable; the value $K_{\dot{z}}$ = .075 at 65 kt, with a linear change to the hover value, was modified from the previous experiment on the basis of the ground simulator tests, even though again the $K_z/K_{\dot{z}}$ ratio did not equal Z_w at this flight condition. The initial series of flights were flown with these gains. As can be seen from the pilot comments in Appendix II, the pilot considered the vertical information not optimized (e.g. Flights F-166, F-167), and in fact appeared to disregard vertical performance to some extent as a result.

As a result, the VTAB gains were modified for flights F-177 to F-181. The ratio $K_Z/K_{\dot{Z}}$ was changed to 0.05 to reflect more closely Z_w of the AV-8B simulation; in addition, the altitude error (K_Z) was increased in sensitivity so that full scale deflection was 75 ft rather than the previous 100 ft. The resulting value of $K_{\dot{Z}}$ in hover was therefore 1.33 volts/ft/sec. Further, the $K_{\dot{Z}}$ at 65 kt was changed to .2 volts/ft/sec so that the ratio $K_Z/K_{\dot{Z}}$ at 65 kt more closely approximated the value of Z_w at this flight condition ($K_Z/K_{\dot{Z}}$ = .325). As the pilot comments for the following flights (e.g. F-177) indicate, these revised gains were considered more satisfactory. Referring to the Bode plots given in Appendix I, the sensitivity of the pilot to vertical guidance problems appears to be high: comparing the two sets of gains for the 1.0 ACAH system at hover, the major difference appears to be an extension of -90^o phase (-270^o on the plot) to somewhat lower frequencies, and somewhat higher amplitude at higher frequencies. Table 6-5 summarizes the two sets of VTAB gains; Appendix I contains the transfer functions of VTAB to throttle.

TABLE 6-5

VTAB GAINS

CONT. SYS.	K_Z(volts/ft)	$K_{\dot{Z}}$(volts/ft/sec):0 kt	$K_{\dot{Z}}$(volts/ft/sec:65 kt	FLIGHTS
ALL	.050	.50	.075	158,159, 160,164-167
ALL	.067	1.33	.20	177-181

6.6.3 Lateral Stick Control Director Logic

The function of the lateral stick director is to provide steering commands to acquire and track the localizer centerline and to assist the pilot in roll stabilizing the aircraft. The logic of this director (VBAR) is therefore expressed in a manner analogous to the longitudinal stick director.

$$VBAR = K_{\dot{y}}\dot{\varepsilon}_{y_h} + K_\phi \phi + K_p P = K_{\dot{y}}(\dot{Y}_{h_c} - \hat{\dot{Y}}_h) + K_\phi \phi + K_p P$$

As was discussed in Section 4, a heading hold directional control system was provided for hover with all control systems investigated in this experiment; with the heading hold system, a washout is added to the bank attitude signal in the above equation to avoid stand-off errors when hovering in a crosswind with a wing down. As with the HBAR logic discussed previously, the $K_{\dot{y}}$ gain was selected a priori; the value $K_{\dot{y}}$ = .1175 volts/ft/sec used in the Reference 2 experiment was again used here (maximum deflection for 42.5 ft/sec error). The gains K_{ϕ} and K_p are then selected to obtain K/S-like behavior over a wide frequency range. Again, K_{ϕ} and K_p are different for different control system implementations, but did not vary with flight condition as implemented in this experiment.

Because one lateral-directional control system was used for all the rate-command-attitude-hold longitudinal systems and one for all the attitude-command longitudinal systems, only three lateral stick control director designs were required (these two plus the AVSAS). The K_{ϕ} and K_p gains investigated are summarized in Table 6-6.

TABLE 6-6
VBAR GAINS

CONT. SYS.	K_p (volts/rad/sec)	K_{ϕ} (volts/rad)	FLIGHT NUMBER
AVSAS	.6017	3.29	158
	14.33	31.51	164
	5.85	31.51	165
	3.9	12.06	166 on
RCAH	.60	1.89	169
ACAH	1.52	3.29	164
	.60	3.29	159, 160, 165
	.60	1.89	166 on

As can be seen, a considerable amount of iteration was involved in the early flights (before F-166) with the gains for the AVSAS system. The K_{ϕ} gain on

F-165 was an experimenter error: the intended gain was 18.09 volts/rad (ratio K_{ϕ}/K_p = 3.1), but the potentiometer setting from the previous flight was erroneously used. The earlier values are a result of calculation errors. The final AVSAS values yield full scale deflections for p = 73 deg/sec and ϕ = 23.8 deg, which are similar to the Reference 2 values for the rate-augmented control system investigated there (and probably should have been used in the first place!).

The effects of these gain changes on the open-loop VBAR responses can be seen in the Bode plots given in Appendix I. Note that hover plots for both the up-and-away directional augmentation and the heading-hold system are given. For the AVSAS with heading hold, it can be seen that the final director gains provide a K/S response from approximately 0.5 rad/sec to 10 rad/sec, thereby including reasonable ranges of pilot crossover; the previous gains are not as good in this regard. The rate-command-attitude-hold gains with heading hold require some pilot lead compensation at mid-frequencies (Phase > 90^{o}); one reason is that the director gains used are for the attitude-hold portion, while the Bode plots are for the attitude/feedback switched out. The differences in the Bode plots among the three sets of gains for the attitude command system can be seen to be minor; this result is typically true: the better the control system, in the sense of stable and smooth aircraft responses, the less sensitivity to control director design.

It will be noted in Tables 6-1 and 6-2 given earlier that the full scale (i.e. 5 volt) deflection of the lateral stick control director is larger, in terms of actual displacement on the display, for the AV formats than it is for the ED formats. This difference means that, for the same director gains, the lateral control director on the AV formats will appear more sensitive to the pilot than on the ED format. Although the overall director sensitivity could have been reduced on the AV formats to make them compatible with the ED sensitivities, this reduction was not included.

6.6.4 Nozzle Rotation Director (ITVIC)

The command logic for the nozzle rotation command (or ITVIC) was described in Section 5 of this report. At the range when airspeed tracking switches to ground speed tracking to initiate the deceleration, the ITVIC logic flashed the aircraft symbol on both AV and ED formats; a light on the instrument panel also came on. Upon moving the nozzle angle lever from the simulated $\theta_j = 70^o$ position (for 65 kt) to the hover stop ($\theta_j = 81^o$), the flashing stopped and the light was extinguished. This command was included in all the formats examined.

Section 7
CONDUCT OF THE EXPERIMENT

7.1 SYNOPSIS OF SECTION

The purpose of this section is to outline the procedures that were used in conducting this flight experiment. The following subsections outline the equipment used, simulation situation, evaluation procedure, and the types of data obtained in the experiment.

7.2 EQUIPMENT

7.2.1 X-22A Variable Stability V/STOL Aircraft

The United States Navy X-22A V/STOL variable stability aircraft was used as the in-flight simulator for this experiment (Figure 7-1). Briefly, the X-22A is a four-ducted-propeller V/STOL aircraft with the capability of full transition between hover and forward flight. The four ducts are interconnected and can be rotated to change the duct angle (λ) and therefore the direction of the thrust vector to achieve the desired operating flight condition defined by a particular speed and duct angle combination. The thrust magnitude is determined by a collective pitch lever, very similar to a helicopter. Normal aircraft-type pitch, roll and yaw controls in the cockpit provide the desired control moments by differentially positioning the appropriate controls in each duct (propeller pitch and/or elevon deflection). A mechanical mixer directs and proportions the pilot's commands to the appropriate propellers and elevons as a function of the duct angle.

The X-22A incorporates a Calspan-designed four-axis (pitch, roll, yaw, thrust) response-feedback variable stability system (VSS) plus a 96-amplifier analog computer designed and fabricated by Calspan. In this experiment, the simulation of the unaugmented AV-8B aerodynamic characteristics was accomplished with the VSS, while the structure of the simulated

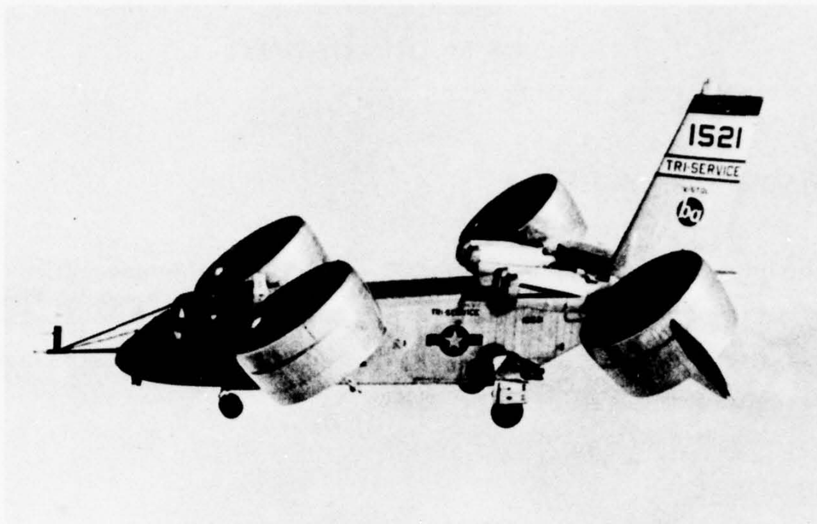


Figure 7-1 X-22A VARIABLE STABILITY V/STOL AIRCRAFT

control systems was performed with the analog computer; the analog computer also provided the duct rotation logic to simulate the AV-8B deceleration characteristics, the guidance command generation, and control director logic. The VSS capability was enhanced by permitting collective action of the elevons within the authority limits of the feed-forward servos ($\pm$3-1/2 degrees), although only feed forward commands (throttle, longitudinal stick, and duct angle positions) were used in this experiment. The evaluation pilot's control inputs (from the left hand seat in this aircraft), in the form of electrical signals, are summed through the analog computer and VSS with the appropriate signals proportional to the aircraft motions to operate the right hand flight controls through electrohydraulic servos. The system operator, who also serves as the safety pilot, occupies the right hand seat, and operates the aircraft through the primary flight control system when the VSS is disengaged. All of the VSS input and response-feedback gain controls are located beside the safety pilot; fourteen potentiometers for the analog computer are located next to the evaluation pilot.

Control feel to the evaluation pilot's stick and rudder pedals is provided by electrically controlled hydraulic feel servos which provide opposing forces proportional to the stick or rudder deflections: in effect, a simple linear spring feel system. Note that the evaluation pilot can not feel the X-22A control motions produced by the variable stability system. For this experiment, the normal collective stick controller for the evaluation pilot was replaced by a fore-aft throttle-type controller to simulate the AV-8B throttle, and a simulated nozzle-angle lever, similar to the AV-8B, was added for the deceleration initiation (Figure 7-2).

A variable head-up display capability was provided for this experiment by adding to the aircraft a Smiths Industries pilot display unit (PDU) in conjunction with a Smiths Industries Graphics Generator and an airborne Data General NOVA 3/12 digital computer. The PDU--which includes CRT, optics, and combining glass--was mounted on a retractable mechanism to assure correct eye-to-glass distance and yet permit clearing the PDU from the ejection envelope. The graphics generator and digital computer provide the capability to generate

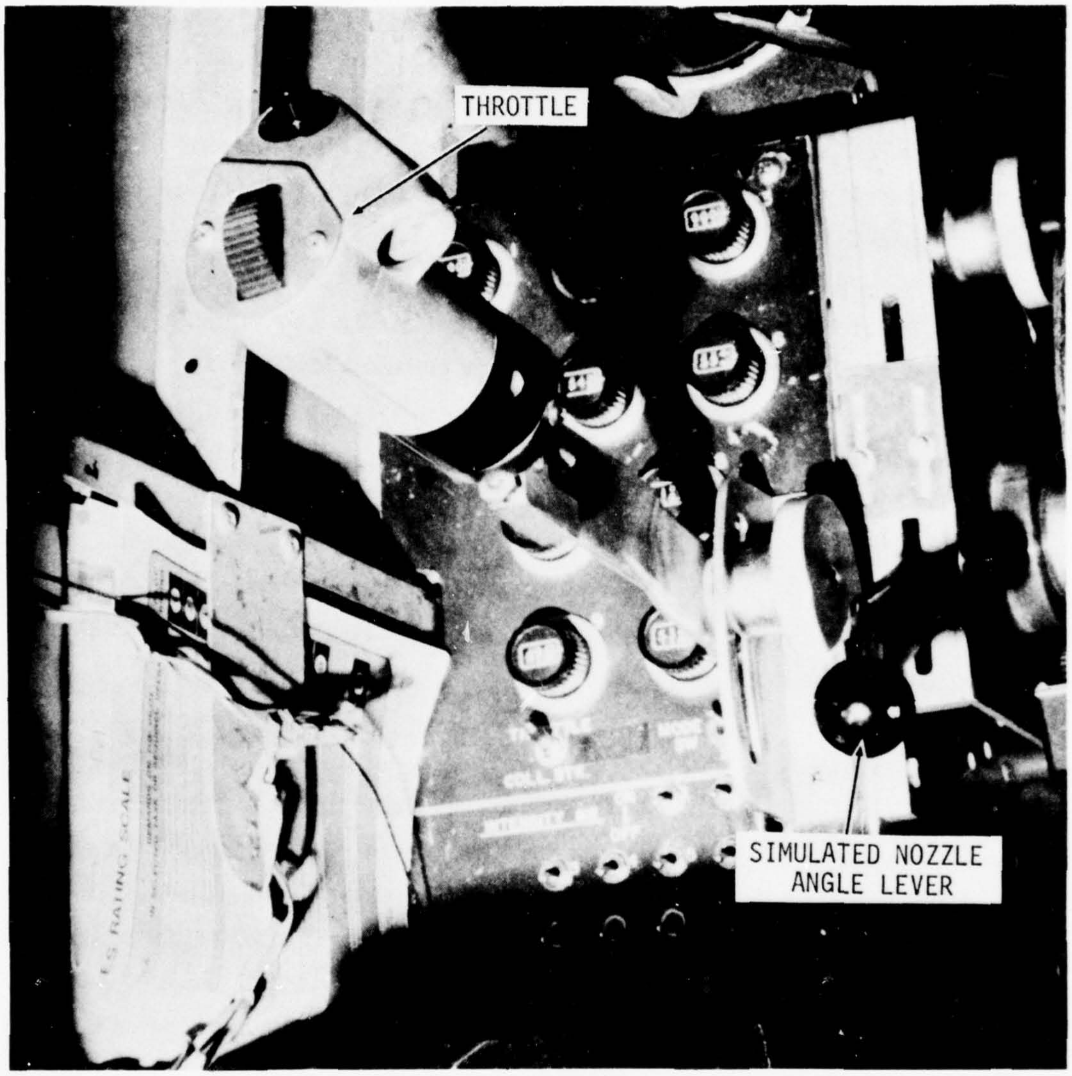


Figure 7-2 SIMULATED NOZZLE ANGLE CONTROLLER

display information formats for either head-up or head-down presentation. Complete programming flexibility permits an essentially unlimited range of calligraphic symbology and alphanumerics for the replication of existing electronic formats or the design of new ones. The computer is controlled from a remote miniature terminal in the cockpit, so that any desired format can be selected in flight. This capability is very important for in-flight research experiments, as different display presentation may be evaluated during flight without landing and reprogramming the symbol generator. The evaluation pilot's instrument panel incorporating the HUD is shown in Figure 7-3.

A more complete description of the X-22A systems is contained in Reference 27 and summarized in Appendix V.

7.2.2 Microwave Landing System

For this experiment, position data relative to the selected hover pad were provided by a microwave landing system (MLS) developed by the U.S. Army Electronics Command and built by the AIL Division of Cutler-Hammer, Inc. This system uses the scanning beam technique and has a co-located DME; airborne equipment in the X-22A decodes absolute azimuth, elevation, and range, resolves it into XYZ position data, and blends it with on-board accelerometer data through complementary filters to provide smoothed estimates of translational positions and velocities. A summary of the resolution and filter equations is given in Reference 28 and Appendix V.

7.2.3 Data Acquisition System

Both experimental and flight safety data were telemetered to and monitored by the Digital Data Acquisition and Monitoring System developed expressly for the X-22A by Calspan and housed in a mobile van. Since the complexity of the X-22A makes it impossible for the pilot to monitor all the important flight safety parameters, it is essential to have ground monitoring of the flight safety variables. The flight safety variables were monitored

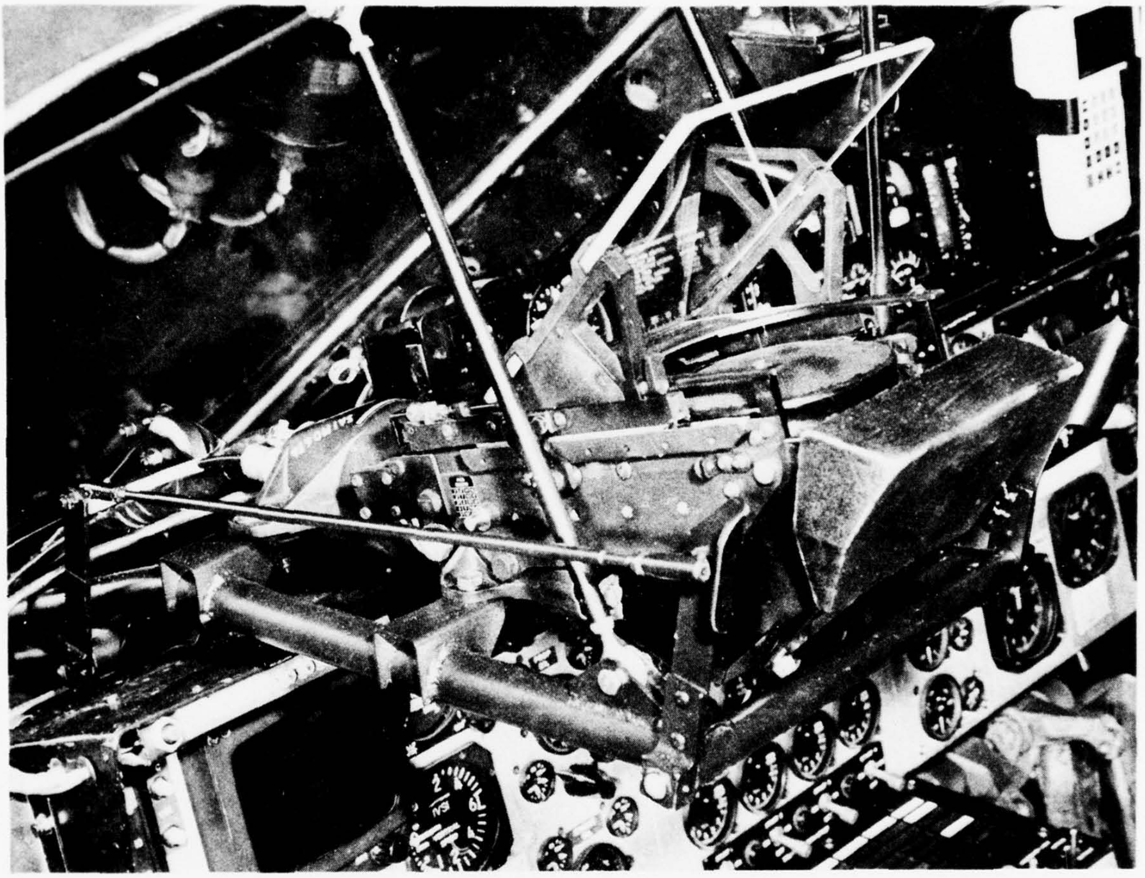


Figure 7-3 HEAD-UP DISPLAY

on chart recorders and by a digital mini-computer in the van. In addition, a continuous recording of all telemetered data, including radar position data and the guidance relationships performed in the analog computer, was obtained on the "bit-stream" recorder for later analysis and processing. During the program, good telemetry coverage was achieved at ranges between the van and the X-22A of up to twenty miles. The details of the Digital Data Acquisition System are covered more fully in Appendix V.

7.3 CONFIGURATION SET-UP PROCEDURE

Prior to the initiation of the evaluation approaches for each configuration, the characteristics of the control-system/display-presentation combination to be investigated were set up in flight by both pilots before engagement of the variable stability system. The set-up functions to be performed by each pilot were listed on a card on each configuration, and are summarized below.

Safety Pilot

- Set all variable stability system gains in thrust, pitch, roll, yaw.
- Select via two-position switch rate-command-attitude-hold or attitude-command when attitude feedbacks were implemented in the control system.
- Select HUD format on remote terminal for digital computer.
- Set selected approach course into digital computer via remote terminal.

Evaluation Pilot

- Set selected approach course on differential resolver (ψ_A).
- Select ON via two-position switch the scheduled duct rotation to be commanded by the nozzle lever.

- Select ON via two-position switch the ITVIC command (light in cockpit ON at deceleration initiation).
- Select OFF via two-position switch control director signals to the head-down ADI needles.
- Select via two-position switch whether or not display had throttle director information.
- Set 14 potentiometers from the analog computer to select control system gains and control director gains.

The evaluation pilot was also provided with a "push-push" switch on the throttle to select the "heading-hold" directional mode in hover; colored lights on the instrument panel indicated which mode was selected. For the ED formats, this switch also selected the reference frame used when heading-hold was selected. This procedure was a carry-over from the previous X-22A experiment (Reference 2) for these formats, but was not used in the AV formats to maintain consistency between those that did not present plan view information and those that did.

As part of the set-up, the evaluation pilot's card provided him with a picture of the display to be evaluated and a description of the symbology. He was not, however, told what control system configuration he would be evaluating, nor whether SAS actuator authority limits were being simulated, nor whether the control-display combination had been previously evaluated.

7.4 SIMULATION SITUATION

To obtain valid flying qualities data in the form of pilot ratings and comments, careful attention must be given to defining, for the evaluation pilot, the mission which the aircraft/pilot combination will perform and the conditions in which it will be performed. For the current experiment, the simulated aircraft was defined as an all-weather set VTOL fighter (Class IV of MIL-F-8330, Reference 9) performing terminal area operations; the aircraft was considered a single-pilot operation but no allowance was made for

typical additional duties, e.g., communications. Additional factors such as passenger comfort were not considered by the pilot in making his evaluation.

7.5 EVALUATION TASK

Although the mission generally involves many elements, an evaluation of the suitability of the vehicle for the mission can be accomplished by having the evaluation pilot perform a series of maneuvers representative of those tasks anticipated in the mission. With the general conditions defined as above, the specific tasks to be accomplished for each evaluation were defined as two simulated-IFR ("hooded") approaches from 65 Kt to the hover, employing a decelerating descending transition. Although it had been planned to investigate a similar profile initiated at 105 Kt, time constraints precluded evaluations of this alternate profile. The elements of the approach profile are summarized below and in Figure 7-4:

- level flight localizer acquisition (1000 ft AGL, 65 Kt)
- constant speed glide slope acquisition (5.0 degrees) at approximately 13,000 ft range
- one-step deceleration initiation on the glide slope, commencing at a range dependent on headwind (zero-wind range approximately 3000 ft)
- flare to level final approach commencing at approximately 800 ft range, final altitude 100 ft, deceleration continuing to hover
- hover to 100 ft above simulated pad, vertical airwork as desired.

An actual vertical landing was not included in the task, and no extrapolation to landing is included in the pilot ratings. The pilot was asked, however, to extrapolate to a pilot rating if the hover was not included in the task; the purpose of this extrapolation was to obtain an estimate of configurations that would be influenced by a breakout to visual conditions.

TASK IV APPROACH PROFILE

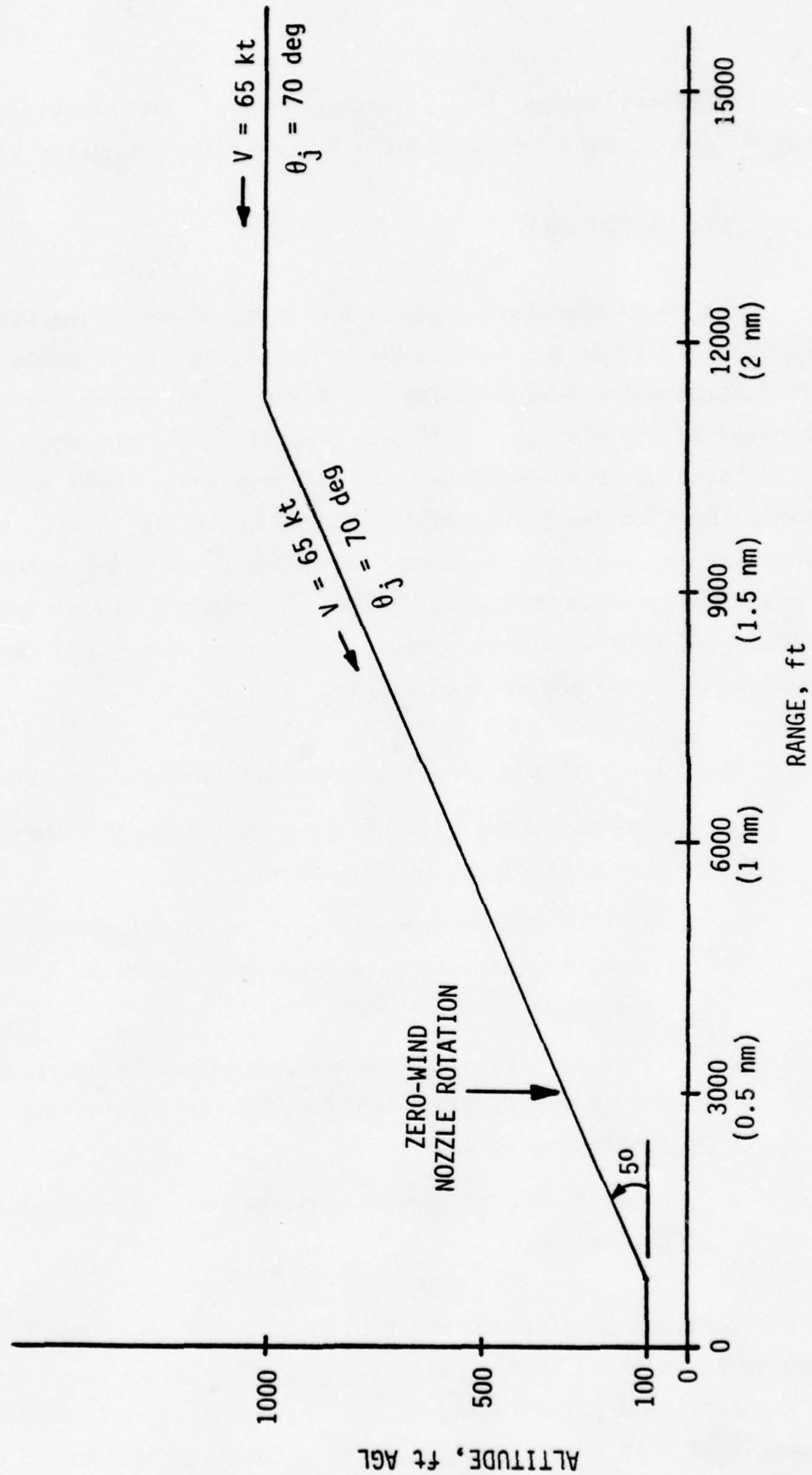


Figure 7-4 65 KT APPROACH PROFILE

7.6 EVALUATION PROCEDURE

The evaluation procedure was as follows. Upon completion of the set-up procedures discussed in Section 7.3, the evaluation pilot went into simulated IFR conditions; in this experiment, IFR conditions were simulated with an amber windscreen on the X-22A and a blue visor on the pilots helmet, so that visual approaches required only the flipping up of the blue visor. The safety pilot then engaged the VSS, generally within the MLS beam but not aligned with the localizer centerline, and the evaluation pilot then performed the approach profile described above. At the conclusion of the first hover, the VSS was disengaged and the safety pilot took the airplane back out to the initiation point; the evaluation pilot then performed a second instrument approach in the same fashion. In this experiment, two configurations included a breakout to visual conditions at approximately 100 ft AGL, 1000 ft range (just at the level off); the remainder involved decelerations to hover entirely on instruments for both approaches of each configuration. At the conclusion of the second approach, the pilot assigned an initial Cooper-Harper pilot rating (Reference 29, Figure 7-5), then tape-recorded comments with reference to a detailed comment card, assigned a final Cooper-Harper rating for the whole approach, assigned (for most of the flights) a turbulence effect rating (Figure 7-6), and indicated what the pilot rating would have been if hover wasn't included.

The pilot comment card is given below. It is important to note that the purpose of this card is to aid both the pilot in performing his evaluation and the analyst in determining the major reasons for the rating. The ratings by themselves only constitute half the data, therefore, and the summary of the pilot comments given in Appendix II must be consulted to obtain a clear understanding of the configuration's suitability for the task.

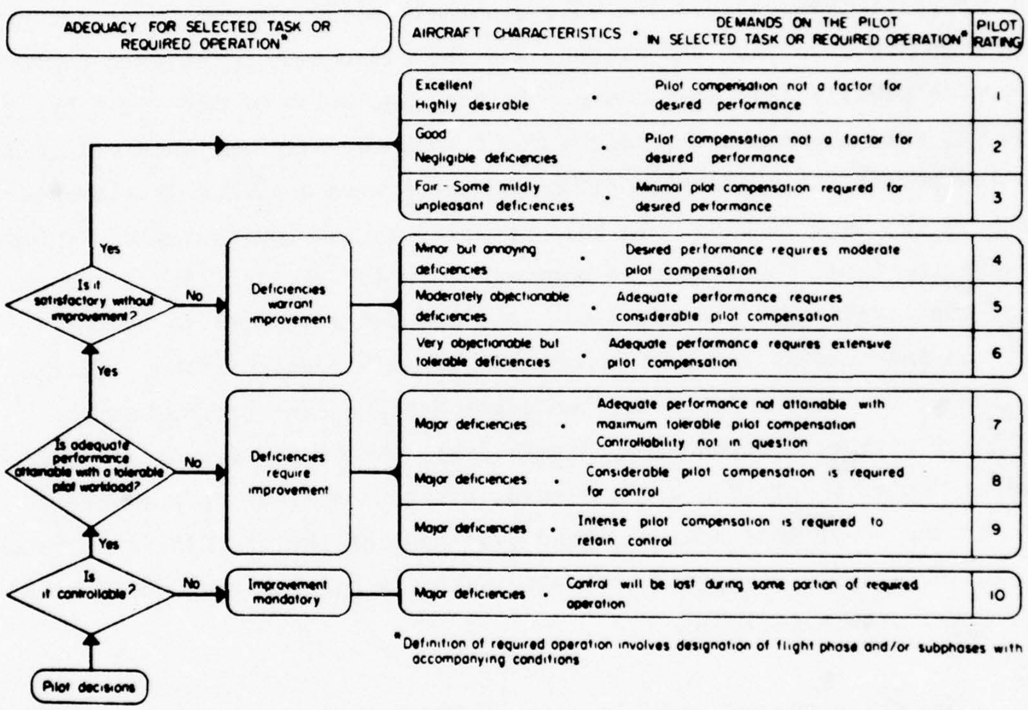


Figure 7-5 COOPER-HARPER PILOT RATING SCALE

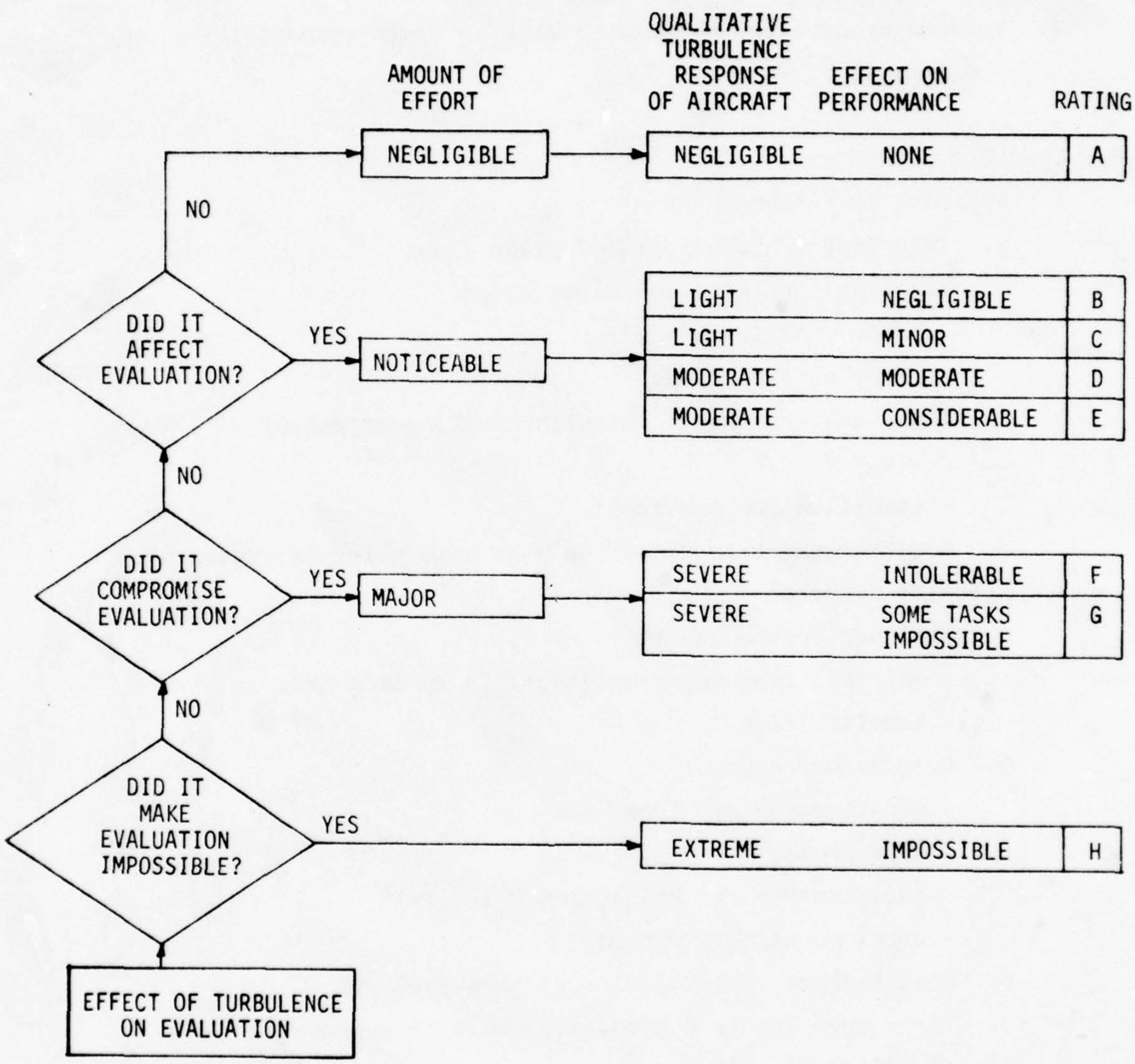


Figure 7-6 TURBULENCE EFFECT RATING SCALE

A. General Comments

1. Assign rating using Cooper-Harper scale
2. Were major problems associated with aircraft response, displays, or you?

B. Specific Comments

1. Approach Performance
   a. Intercept of localizer and glide slope
   b. Tracking localizer and glide slope
      - before nozzle change
      - after nozzle change
      - any concerns about velocity tracking or range?
   c. Hover
      - stabilization problems?
   d. Would breakout to visual help at some point of approach?
2. Aircraft Response
   a. Attitude (pitch and roll)
      - initial response, predictability in each axis
      - sensitivities
   b. Directional control
      - coordination problems?
   c. Thrust Control
      - satisfactory for height (or velocity)?
      - cross-coupling problems?
   d. Longitudinal velocity control satisfactory?
   e. Turbulence inputs a problem? Where on approach?
3. Displayed Information
   a. Electronic display
      - any interpretation problems?
      - sensitivity?
      - command information satisfactory?
   b. Additional instruments
      - any other ones used?
      - scan problems?

C. Summary Comments

1. Pilot rating (entire task including hover)
   - dichotomous decision process, descriptive words best suited.
   - identify deficiencies most influencing rating
   - agree with initial rating?
2. Pilot rating if hover not included. If different, why?
3. Turbulence effect rating

7.7 DATA ACQUIRED

The data acquired from this experiment falls into the following categories:

1. Pilot ratings and comments
2. Wind and turbulence
3. Aircraft response
4. Tracking performance

Data on aircraft responses were required to estimate the achieved simulated characteristics; the identification procedures are summarized in Appendix III. An estimate of ambient headwind/tailwind and crosswinds is required to interpret some of the pilot ratings and comments; this information is summarized in Appendix IV. Detailed analyses of tracking performance data were not conducted, but some of the raw information is also contained in Appendix IV.

7.8 EVALUATION SUMMARY

Because of the relatively limited flight time available for evaluations in this program, only one evaluation pilot was used. He is a Calspan Research Pilot with extensive experience as an evaluation pilot in flying qualities investigations. His flight experience of 4500 hours includes over 650 hours in helicopters, and he is qualified in the X-22A aircraft.

A total of 36.4 hours was flown in this research program, of which 15.7 hours were devoted to evaluation flights; the remaining hours were devoted to checkout and calibration plus 5.0 hours for simulation validation using two Marine pilots. A total of 43 evaluations of 22 control-display combinations was obtained in the program.

Section 8
FLYING QUALITIES RESULTS

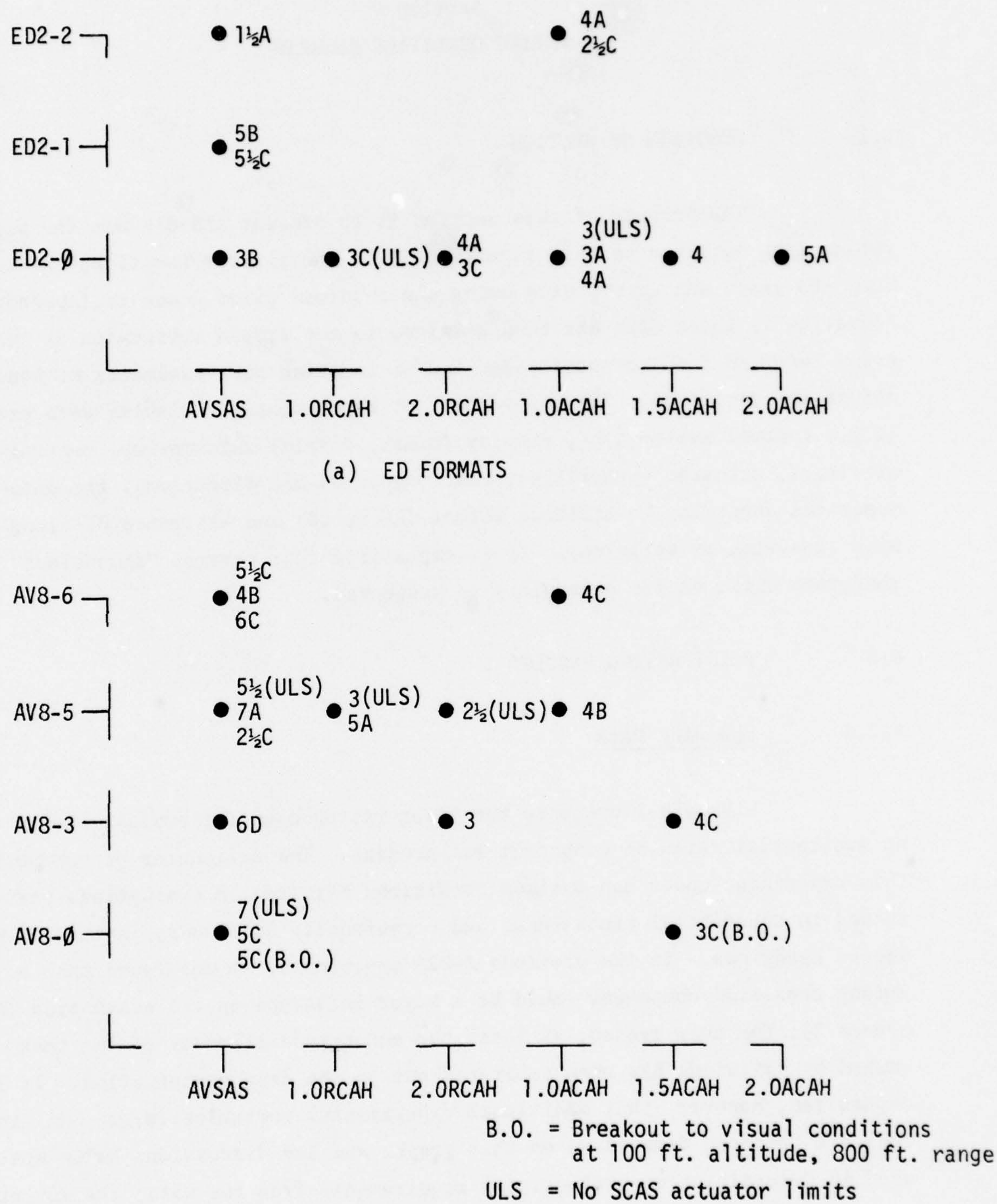
8.1 SYNOPSIS OF SECTION

The purpose of this section is to present and discuss the pilot rating data obtained in this experiment. In the first subsection, the rating data are given and interpreted using the recorded pilot comments (Appendix II). Anomalies in these data are then examined in the second subsection by considering recorded SCAS actuator usage and/or limiting plus estimates of wind magnitude and direction. Since a variety of experimental variables were examined (e.g., control system type, display format, display information, control sensitivities, actuator authorities, wind magnitude and direction), the data are separated according to attitude format (AV or ED) and estimates of along-track wind (headwind or tailwind). It is emphasized that several "dimensions" will therefore exist on the data plots as presented.

8.2 PILOT RATING RESULTS

8.2.1 Headwind Data

Figure 8-1 presents the pilot rating data for evaluations in which no substantial tailwind component was present. The exigencies of conducting this experiment under non-optimum conditions resulted in evaluations being obtained in substantial crosswinds, and occasionally tailwinds, instead of preferred headwinds. In the previous X-22A experiment, it was found that a strong crosswind component could be a major influence on the evaluation (Reference 2); for this reason, at least the enhanced difficulty of the task caused by tailwinds has been separated out in the data presentation. It is emphasized, however, that additional experimental variables (e.g., SAS limiting) are "hidden" dimensions on this graph, and the discussions below must be used in determining control-display requirements from the data; the intent in presenting all the data together is to facilitate an overall understanding of some of the influences.



(a) ED FORMATS

(b) AV FORMATS

Figure 8-1 PILOT RATING RESULTS (HEADWIND)

One immediately seen result is that the hypothesized rank ordering of the display information and control system "goodness" on the plots does not appear to demonstrate a control-display tradeoff to the consistent extent seen in the previous X-22A experiment (Figure 1-1). To some extent, this result may be due to the concentration on rate and attitude command systems coupled with less marked information differences among the displays. The issue is clouded, however, by additional experimental dimensions, such as control gearings or flight director sensitivity, so that examination of the pilot comments is required to understand the lack of tradeoff. The following paragraphs will address this point via discussion of individual configurations.

It is clear that the proposed AV-8B HUD format (AV8-Ø) in combination with the basic rate-damper SAS (AVSAS) is unsatisfactory for the instrument approach task even if the final deceleration (from 30 kt) and hover are done under visual conditions. The major reasons are lack of assistance with controlling pitch attitude and velocity from the display given the response characteristics with this control system:

PR = 7 (no breakout)	:	"Got lost in hover, don't have sufficient information. [Don't know] where I am relative to the pad. Velocity [on this display] not relative to the ground." (F-158)
PR = 5C (no breakout)	:	"Weird, could do job in hover but felt I should be lost. Only problems were with flight director, have no assistance handling pitch attitude, seemed useless for height control. Hover breakout would help, but still wouldn't like flight director [being throttle and lateral stick]." (F-167)

PR = 5C (with breakout at 30 kt) : "Velocity tracking hard because of display format. Difficult to follow thrust director. Have to hold pitch attitude independently, get mixed up occasionally and follow director with longitudinal stick." (F-178)

The control system transfer functions (Appendix I) show that, in pitch at 65 kt, the aircraft with the AVSAS control system has a positive real root; the difficulty with the AV8-Ø format appears to be a problem for the pilot in using the attitude information as presented to stabilize this root in the absence of other information to assist him. The difficulty of controlling longitudinal velocity is further exacerbated by the pilot occasionally associating vertical motions of the flight director symbol with longitudinal control commands.

One possible improvement, therefore, is to rearrange and add to the information contained in the AV format to assist with the pitch control task. The AV8-3 format does so by adding a longitudinal stick director to the AV8-Ø information (Section 6.4); as can be seen, however, the AVSAS/AV8-3 configuration received a PR = 6. Part of the problem was flight director sensitivities as discussed in Section 6; additionally, however, the pilot ran into directional control problems (the AVSAS uses very low lateral acceleration feedback - Section 4) and continued to complain about pitch precision and the lack of position status data with the AV8-3 format:

PR = 6D : "Am not happy with flight director. Tendency to overcontrol in pitch. Directional coordination also a problem, got hung up with ball out. Concerned about pitch precision with this format. Do not like not having position status information." (F-165)

Apparently, therefore, the fact that the aircraft response characteristics with the AVSAS control system result in a sensitive control director design places emphasis on the need for additional status data.

The AV8-5 format presents analog information about both ground-referenced velocities and positions in lieu of control director information; hence, questions concerning the director design sensitivity are circumvented, and the information presented meets the minimum requirements found in the previous X-22A experiment (although this information was found insufficient with rate-damping-only control systems in that experiment). The ratings for this format with the AVSAS control system vary from 2-1/2 to 7, showing if nothing else the high sensitivity of the pilot-display-aircraft to atmospheric conditions and probably pilot technique:

PR = 2-1/2C	:	"A bit twitchy but very responsive, easy to control. Some problem with crosswind getting into hover. Got the ball out, have to change heading to contend with crosswind. Velocity tracking super after get heading cranked around." (F-179)
PR = 5-1/2	:	"Turbulence caused major problems. Could not get heading settled down. Display lacking in precision with which you can judge pitch attitude. Some lack of precision of trim in pitch." (F-162)

PR = 7A : "Directional got messed up midway through transition. Got cross-control, hard to center the ball. Roll attitude doesn't come through well with this display, had trouble with localizer. Turbulence not a factor." (F-163)

From the comments, it appears that the extent to which sideslip gets excited varies and is a major contributory factor in the ratings with the AV-8B SAS. As with the AV-8A, the lateral acceleration feedback to the rudder is very low, and the aircraft's unaugmented characteristics demonstrate very little directional stiffness. The pitching difficulty is exacerbated by a fairly high dihedral effect, so that sloppiness in sideslip control caused by the low directional stiffness leads to increased roll control difficulties. It is likely that, in these three evaluations, the degree to which the pilot concentrated on sideslip excursions and heading tracking varied — perhaps because of different setups initially relative to the localizer and glide slope — and hence the influence of the sideslip on the aircraft characteristics varied in impact. It is clear, however, that the AVSAS/AV8-5 configuration is too sensitive to these variations to be considered suitable.

Adding three-axis control directors plus analog velocity and position information to the AV format (AV8-6) does not alleviate the problems either if the AVSAS control system is retained. The AVSAS/AV8-6 configuration received ratings of between 4 and 6; the major complaints concerned the flight director. While the ratings PR = 4 and PR = 5½ were obtained prior to the finalized sets of director gains, the PR = 6 was obtained for the same ratios on the director gains as the PR = 1½ with the ED2-2 format.

PR = 4B : "Localizer [intercept] easy with flight director, glide slope seems to be chasing the index. Directional only a problem contending with cross-wind at end. Velocity tracking good once you got turned [into wind]. Height control not satisfactory." (F-166)

PR = 5-1/2C : "Directional control at end a big problem. Flight director not good. Directional cross-control at start of transition and at end is very disconcerting, directional workload high. Really had problems with my feet." (F-165)

PR = 6C : "Don't like flight director, don't like it compared to the one I've seen before [ED2-2]. Had concerns about velocity tracking. Directional O.K. with some tendency to lose heading and get ball out." (F-179)

On the basis of the preceding discussions concerning the ratings for the AVSAS control system in combination with display formats based on the proposed AV-8B HUD (3:1 pitch scaling, pitch ladder with broken rungs), the following inferences can therefore be drawn:

1. The AV-8B with the AVSAS exhibits control characteristics in pitch that require stabilization by the pilot. The attitude presentation with the AV formats does not appear to assist the pilot consistently in this regard, nor does the longitudinal stick director as it was implemented on this format in this experiment.

2. The AV-8B with the AVSAS is "sloppy" directionally. The suitability of this control system for instrument transitions with any of the AV formats appears very sensitive to pilot technique plus atmospheric conditions (wind magnitude and direction).

3. The addition of analog presentations of velocity and position data to the AV format does not, by itself, provide consistent improvements in pilot ratings if the control system is the AVSAS.

4. The basic AVSAS/AV8-Ø configuration is unsatisfactory for transitions to hover entirely on instruments and is also unsatisfactory when the deceleration on instruments is only from 65 kt to 30 kt.

Consider now the AVSAS in combination with the ED formats. Recall that the information content on ED2-Ø in terms of positions and velocities is the same as AV8-5, and that on ED2-2 is the same as AV8-6; the difference between the formats is that the ED displays are based essentially on head-up presentation of ADI attitude information (16:1 pitch scaling, one solid horizon bar, roll index at the top of the display, flight director bars that are similar to ADI needles). Although the headwind evaluation data are not as extensive as for the AV formats, the results are interesting, both because of the contradictions with the AV format results and contradictions with the results of the previous X-22A experiment.

The AVSAS/ED2-Ø configuration received a PR = 3 for the entire approach to hover:

PR = 3B : "More concerned about crosswind than had to be. Could fly with confidence. Smooth and predictable in both axes (roll and pitch). Some directional concerns but no coordination difficulty." (F-167)

These comments are similar to those given with the PR = 2½ rating for the AVSAS/AV8-5 configuration. What is interesting is that the attitude control is called smooth and predictable with the ED format, while it seemed twitchy although easy to control with the AV format. To the pilot, the attitude response characteristics are judged by what he sees on the display when on instruments; the difference in pitch attitude scaling between the ED and AV formats frequently appeared to the pilot as different airplane characteristics, as will be discussed at more length later in this section.

With three-axis control directors, the ED format in combination with the AVSAS control system (AVSAS/ED2-2) received the best rating given in the experiment:

PR = 1-1/2A : "Easy to fly, flight director did a good job, good conditions today. [Tracking] easy. No problems pitch, roll. Directional not even noticed." (F-178)

The differences between these comments and those for the PR = 6 rating with the AV8-6 display are marked; in both cases the flight director gain ratios were the same, but the overall sensitivity (full scale deflection motion on the display) was four times as great on the AV format as on the ED format. Again, the sensitivity of the aircraft control characteristics with the AVSAS control system can be seen to require extremely careful tuning of the flight director commands, not only with respect to the design philosophy but also to the display scaling.

The "mixed" ED format, ED2-1, which provides a throttle director but no pitch or roll stick director, apparently caused more problems than it cured, when used in conjunction with the AVSAS control system:

PR = 5-1/2C : "Couldn't be as precise as desired, problems with airspeed control on approach, interaction between throttle and pitch attitude. I didn't seem to be connected to pitch attitude and velocity. Seemed to see coupling between pitch and thrust." (F-178)

PR = 5B : "Seemed to make large pitch changes, working in pitch a lot, but I don't really think pitch itself a problem. Thrust control, display wanders around too much. Longitudinal velocity satisfactory except for that short time in middle of transition." (F-166)

A primary cause of the degraded ratings with this format is the pitch-to-throttle coupling of the AV-8B combined with a single director that focuses the pilot's attention on throttle inputs. Since no pitch attitude stabilization is provided by the AVSAS control system, the increased throttle activity caused by the director leads to increased pitch excursions and a concomitant degradation in velocity tracking. With this type of control system and aircraft characteristics like those of the AV-8B, it appears from the ED2-1 as well as the AV8-Ø results that providing a throttle director without assistance for pitch tracking is not a good idea.

The results obtained with the ED formats in combination with the AVSAS control system imply the following points:

1. Although the ED format data are limited, ED2-Ø and ED2-2 results contradict the findings of the previous X-22A experiment (Reference 2), in which a rate-damping control system was found unsatisfactory for the decelerating instrument transition regardless of display sophistication. A possible explanation is the difference in difficulty between the pilot's deceleration control task between the two experiments. In the Reference 2 approaches, the pilot made continuous thrust angle changes throughout the approach in response to the ITVIC director; hence, closed loop operation of an additional controller was required. In the current experiment, the deceleration was initiated with a "one-step" command, and the resulting deceleration was open-loop as far as the thrust angle controller is concerned. It may reasonably be hypothesized, therefore, that the reduced workload in the thrust angle axis permitted increased attention to attitude and velocity tracking with the AV-8B simulation.

2. While the data are not conclusive, it appears that the ED presentation of attitude and control director information has some advantages over the AV presentation when combined with the AVSAS control system. Pilot comments from other configurations to be discussed shortly frequently complain about imprecise attitude information with the AV formats, and praise the precision obtainable (from the pilot's viewpoint) with the ED formats.

3. Taking the ratings for the AVSAS control system in combination with all the AV and ED formats, the ratings obtained in headwind conditions indicate that this control system is not suitable for instrument transitions. While the ED2-Ø and ED2-2 ratings might be considered to belie this conclusion, it is clear from the AV ratings that the aircraft characteristics obtained with this control system make for a display/aircraft combination that is sensitive to atmospheric conditions and pilot technique.

It appears, therefore, that providing the AV-8B with an instrument transition capability cannot be done consistently through display improvements alone, and that some improvements to the aircraft's response characteristics are warranted. A good example of the improvements that can be effected by changing the control system even with the basic display is afforded by the 1.5 ACAH/AV8-Ø configuration (PR = 3 with a breakout of 30 kt, 100 feet AGL, 800 feet range):

PR = 3C (with breakout)	:	"Very stable. [Intercept] no problem — lots of time with airplane control characteristics to concentrate on flight director. Thrust no difficulties — could give it lots of attention. Velocity good. Didn't mind strange use of hands on flight director because could devote attention to it." (F-179)

This configuration was also evaluated for instrument deceleration all the way to hover in a slight tailwind (Figure 8-2, to be discussed shortly) and rated a PR = 7, but the major complaint was the lack of displayed information for hover: the pilot estimated a PR = 3 rating if the hover were visual, which corresponds to the rating given in the evaluation discussed above. As was found in the previous X-22A program, attitude command augmentation is very

desirable for decelerating instrument transition; in this case, at least, this level of augmentation could be achieved within the AV-8B actuator authority limits without significant saturation, and the result was a configuration that was satisfactory as opposed to adequate with the AVSAS.

As can be seen from Figure 8-1, the data obtained for the remaining control-display combinations (control systems other than AVSAS, displays other than AV8-Ø) show no significant trends. In general, the ratings are borderline satisfactory (PR = 3 or PR = 4), with little apparent influence of either control system or display presentation. To address this situation, consider first the ratings for the ED2-Ø format for all the control systems:

PR = 3C (1.0 RCAH)	:	"Velocity tracking no real concern — had to pay attention to pitch attitude. No complaints pitch and roll. Directional not a factor. Mildly unpleasant deficiency is pitch response in transition." (F-178)
PR = 3C (2.0 RCAH)	:	"Tendency to pulse stick on approach, but might want more sensitivity in hover. Could track velocity vector until very end, tendency to overshoot [hover pad] but easy to overcome and stabilize. No directional problems." (F-168)
PR-3A (1.0 ACAH)	:	"A little sensitive [in roll], minor tendency to overcontrol. Intercept about as good as I wanted. Had very precise control of the display of pitch attitude. Directional not a factor. Like attitude display, easy to avoid overcontrol." (F-163)

PR = 4 (1.5 ACAH)	:	"Major problems associated with turbulence and roll response. Jerky in roll, lateral forces for steady turns a pain. Directional no problems noted. Thrust'satisfactory. Really like pitch attitude precision with this format." (F-167)
PR = 5A (2.0 ACAH)	:	"Abrupt initial response in pitch and roll on approach, didn't notice in hover. Had to make large pitch changes near end of transition, couldn't make them fast enough, workload high. Tendency to overshoot, difficult to stabilize. No directional problems." (F-168)

For the 2.0 ACAH configuration, a high pitch control gearing was used; this level of gain was too high and so the comments are relevant only to note this fact. The comments for the remaining control systems with the ED2-Ø display are similar in most regards. It is particularly important to note that all the comments indicated no directional problems, in contradistinction to the AVSAS comments. Both the RCAH and ACAH lateral-directional augmentation use a feedback of n_y to the rudder that is approximately eight (8) times higher than in the basic AVSAS. This design parameter was selected on the basis of the previous X-22A experiment results, which indicated the need for enhanced directional stiffness, particularly in crosswinds (Reference 2); the result of the increased directional stiffness in the current experiment is also less sensitive to atmospheric conditions and/or pilot technique, as evidenced by the comments. It is possible, in fact, that reducing the directional "sloppiness" of the AVSAS control system itself by increasing the n_y feedback would provide more satisfactory response characteristics by reducing sideslip excursions.

Considering the three control systems evaluated with the AV8-5 format shows similar consistence in the comments, although the scatter of the ragings is higher:

PR = 5A (1.0 RCAH)	:	"Oversensitive in roll. Tendency to overcontrol in pitch too. Feeling of reasonable confidence with airplane. Directional not a factor. Don't like pitch ladder, but chevrons do help. Do not like bank attitude display." (F-163)
PR = 3 (1.0 RCAH)	:	"Aircraft a little too sensitive in pitch and to some extent in roll. Don't like the pitch presentation with this display. No directional problems noted except turbulence, crosswinds. Still don't like attitude presentation." (F-162)
PR = 3A (2.0 RCAH)	:	"A little extra work in pitch. Had a lot of confidence flying it. Roll good in all respects. Pitch trim drift a small problem. Directional satisfactory." (F-177)
PR = 4B (1.0 ACAH)	:	"Pitch attitude sensitive. Didn't like pitch display. Tendency to overcontrol pitch in hover. No directional problems." (F-167)

Although no important trends appear to be exhibited by these data, a variety of detailed points can be observed. It will be noted that the comments with AV formats point out pitch and/or roll sensitivity (control gearing)

problems more frequently than those with the ED formats. In some cases, the issue is confusing because the control sensitivites were in fact different. An excellent example, however, of the influence of the attitude format is given by comparing the comments for the 1.0 ACAH/AV8-5 configuration with those for the 1.0 ACAH/ED2-Ø configuration that received a PR = 4A; in this case, pitch and roll control gearings were exactly the same, and yet the comments with ED2-Ø were:

PR = 4A (1.0 ACAH)	:	"Pitch sensitivity too low. Couldn't get nose up fast enough at end. Roll satisfactory. No directional problems. Particularly like pitch attitude precision [of the ED2-Ø display]." (F-168)

One result of contradictory comments like these was some unnecessary variations in control sensitivity on the part of the experiment designers! Fundamentally, of course, the point to be made is that, to the pilot in the simulated IFR environment of this experiment, the control sensitivities of the aircraft are judged only by the motion of the attitude presentation on the display. The difference by a factor of 5 in the pitch attitude presentation sensitivities of the two formats examined in this experiment can therefore manifest itself as differences in the aircraft, or controlled element, characteristics even when they are constant. The importance of tuning the two aspects (display sensitivity and control gearing) to each other is evident.

The data for control systems other than AVSAS and display presentations other than AV8-Ø therefore infer the following points:

1. To the extent investigated in this experiment, no clear preference between rate-command-attitude-hold (RCAH) and attitude-command (ACAH) control system implementations was observed.

2. For the range of control system types and display presentations evaluated, no distinct interaction or trade-off was found.

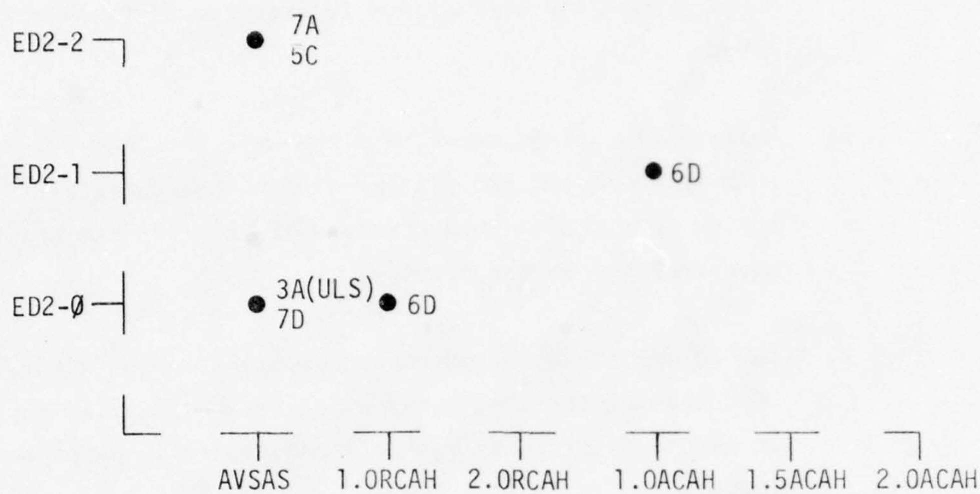
3. Ratings of satisfactory (PR ≤ 3½) were obtained for both RCAH and ACAH control systems with no control director information when analog presentations of velocity and position were included on the display.

4. The ED formats elicited fewer complaints about aircraft control sensitivity. An interaction between display sensitivity in pitch and aircraft control sensitivity in pitch was observed.

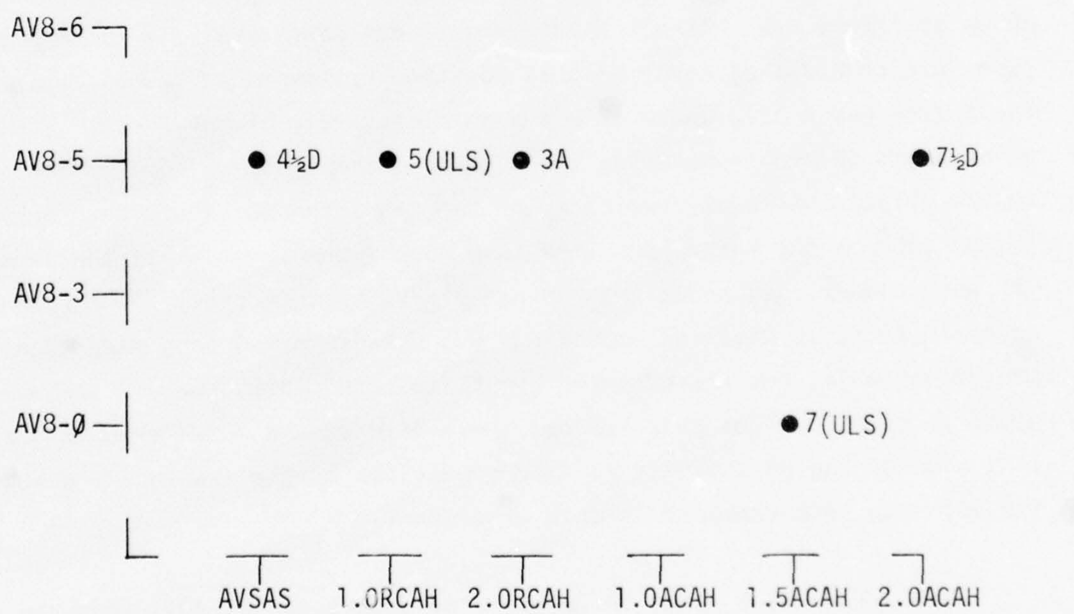
8.2.2 Tailwind Data

Evaluations performed when a tailwind component was present are shown in Figure 8-2. In the X-22A, relatively large positive pitch attitudes are required at hover to hold position against a tailwind (approximately one degree per knot), which is not a characteristic of the AV-8B. The large hover attitude requirements in the nose-up direction were very objectionable to the pilot; this characteristic, or the resulting necessity to change heading by 180° in the hover, resulted in a more demanding task in the simulated IFR environment, and hence the ratings are shown separately. The conduct of evaluations in tailwind conditions was not performed as a planned experimental variable, but was dictated by limited windows in weather and approved approach courses. For this reason, these data should serve primarily as an indicator of the sensitivity to wind conditions of the instrument decelerating approach task examined in this experiment.

The major point to be observed from these data is that the ratings for the AVSAS in combination with the ED2-Ø and AV8-5 formats are still scattered; it can also be seen that the AVSAS/ED2-2 configuration, rated a PR = 1½ in good conditions, is now rated PR = 5 and PR = 7, indicating



(a) ED FORMATS



(b) AV FORMATS

Figure 8-2 PILOT RATING RESULTS (TAILWIND COMPONENT)

inadequate performance. The additional problems created for the pilot by tailwinds are indicated in the comments for these five AVSAS configurations:

PR = 5C (ED2-2) : "Had trouble with glide slope getting organized between throttle and pitch. Directional some weird wind conditions but no real complaints." (F-181)

PR = 7A (ED2-2) : "Display didn't make sense. Some problem trimming aircraft directionally. Problems with crosswind at end." [Also had problems with display discrepancies between directors and position on this configuration.] (F-164)

PR = 3A (ED2-Ø) : "Fathoming wind at end a problem. Concern with slipping by pad because of wind. Trouble getting to center (of pad) because wind made it a two-axis problem. Directional problems in hover trying to get over spot. Am not paying much weight [for giving a pilot rating] to problems I had near the end because of the wind." (F-177)

PR = 7D (ED2-Ø) : "Airplane poor directionally, airplane didn't seem very stable in pitch on approach. Hover difficult, wind is fighting me. Couldn't do good job. Could not do job in hover adequately." (F-181)

PR = 4-1/2D (AV8-5) : "Have to hold big nose high attitudes to station ourselves in hover because of wind, adding measurably to workload. Had to concentrate on glide slope more than desired, things happening faster. [Had to anticipate nose-up requirement for hover]." (F-181)

It is apparent from the comments that the PR = 3 given the AVSAS/ED2-Ø configuration was an extrapolation by the pilot and neglected the problems he had that were caused by the wind; some of the anomaly between the two ratings for this configuration may be explained on this basis. The tailwind component generally created additional glide slope tracking problems (higher rate of descent required) in addition to difficulties in the hover, and hence a degraded pilot rating, for configurations with the AVSAS control system.

For the other control systems which show a degraded pilot rating relative to the data on Figure 8-1, the tailwind component is also a problem, although other factors enter in. For example, the 2.0 ACAH/AV8-5 configuration encountered actuator authority saturation with a concomitant degradation in aircraft response characteristics, and the 1.5 ACAH/AV8-Ø configuration was downrated for the lack of displayed position and velocity data in hover, as was discussed previously. Note, however, that the 2.0 RCAH/AV8-5 configuration was not downrated:

PR = 3A : "Tracking not a problem, wind made tracking localizer funny. I was aware of tailwind problem, got nose up early in transition. Wind made entering hover a challenge." (F-177)

It is not reasonable to attach too much significance to this single data point, but it does appear that the well-augmented characteristics of this control system may have rendered the task performance less susceptible to tailwind conditions.

8.3 ADDITIONAL DATA

As discussed in Section 8.2, the pilot rating data of this experiment were influenced by factors other than the primary experiment variables, (control and display configuration). Variations in control sensitivity (gearing), simulated SCAS actuator authority, and the vagaries of ambient wind and turbulence were additional experiment parameters which, in some cases, introduced apparent anomalies in the rating data. In the subsections to follow, the influence of these additional factors on the experimental results are discussed.

8.3.1 Ambient Wind and Turbulence

Because of the high drag damping of the X-22A, the data discussed in Section 8.2 was segregated according to the ambient wind conditions. Tailwind data was treated as anciliary information because the large nose up attitudes required to hover the X-22A are disconcerting to pilots and are not characteristic of the AV-8B.

The previous X-22A experiment (Reference 2) indicated that crosswinds also caused considerable control difficulty in hover and low speed for configurations with little directional stability. Although the AVSAS configurations have augmented directional stability, the "stiffness" is relatively low. Furthermore, pilot commentary for many of the AVSAS evaluations pointed to directional control problems (difficulty controlling ball excursions, crossed controls). For these reasons, a detailed examination of ambient winds for the AVSAS evaluations was conducted to assess the impact of crosswinds and turbulence on the data. Of particular interest was the poor repeatability of ratings for the AVSAS/AV8-5 control/display configuration, and the differences in pilot ratings between the two flight director formats (ED2-2 versus AV8-6) and the position plus velocity displays (ED2-Ø and AV8-5).

The following table summarizes average values of the components of wind and turbulence relative to the approach course centerline for the

TABLE 8-1

AMBIENT WINDS AND TURBULENCE FOR EVALUATIONS OF
ED2-Ø and AV8-5 DISPLAY WITH AVSAS

Display	Headwind (ft/sec)	Turbulence (ft/sec)	Crosswind* (ft/sec)	Turbulence (ft/sec)	Flt.	PR
ED2-Ø	14.2	2.8	7.5	5.1	167	3B
AV8-5	29.6	4.7	-17.9	5.7	162	5.5
	16.7	3.2	7.6	3.2	163	7A
	11.3	3.3	7.1	4.2	179	2.5C

* Positive for wind from the pilots left

position plus velocity display evaluations. The turbulence magnitude is the RMS value of the random wind components parallel and perpendicular to the approach course. It can be seen from this table that Flights 167, 163 and 179 were flown under nearly identical wind and turbulence conditions but the rating for Flight 163 was significantly at variance with other two flights. The pilot comments (Appendix II) suggest that differences in pilot technique for coping with crosswind during transition may be responsible for the marked differences in rating. On Flight 163 (PR = 7A) the pilot complained of directional problems in transition, getting cross controls (i.e. sideslipping with wing down) and increased lateral tracking errors in transition which were exacerbated by the poor perception of bank angle afforded by the AV-8 display. The fact that the pilot estimated that the rating would be 4 to 5 if he had broken out at 200 feet (i.e., transitioned visually) confirms that the problems in transition dominated the rating.

In contrast, on Flight 179 (PR = 2.5C) the pilot indicated that he had some directional problems in transition but after changing heading to contend with crosswind (crabbing), the velocity tracking was "super." Overall, the airplane was described as responsive, easy to control. The pilot's comments for Flight 167 reflect similar confidence in the aircraft and his ability to perform the task. His procedure for dealing with the crosswind is

not specifically described although concern about crosswind in transition is mentioned, i.e., " More concerned about crosswind than had to be.....over-anticipated and made my own problems." These comments, together with the known ambient wind conditions suggests that the poor rating for Flight 163 is attributable to crosswind technique. On this flight, as the aircraft decelerated during the transition, the pilot attempted to track the approach course by sideslipping and banking as opposed to crabbing (i.e., heading into the wind). It is surmised that sideslipping is a more difficult technique in that pedal control is required but no explicit error signal associated with the pedals is displayed and precise control of bank angle is difficult with the AV-8 display format. Furthermore, the controls are crossed ($L_v < 0$) requiring unnatural coordination of the roll stick and pedal control inputs. Finally, the continuous lateral acceleration in the wing down approach is uncomfortable to the pilot and detracts from performance in the other axes. On Flight 162, the magnitude of the ambient winds and turbulence is considered to be the major contributor to the deterioration in pilot rating rather than the control technique difficulties experienced on Flight 163. Complaints about the turbulence and its effect on localizer tracking dominate the pilots comments although the lack of precision of the pitch attitude display format is also cited as contributing to poor velocity control.

In summary, it is apparent that under ideal conditions (i.e., low ambient winds and turbulence and the preferred control technique) both the AV8-5 and ED2-Ø display formats will provide satisfactory flying qualities with a rate damping only SCAS for the airframe dynamics considered in this experiment. The rating variation observed for the AV8-5 formats is attributable to variations in ambient winds and turbulence and pilot control technique together with display characteristics such as the ladder presentation of pitch and roll attitudes employed with the AV8-5 format. Thus, under less than optimum conditions, consistent Level 1 ratings would not be achieved with the AV8-5 display and this control system; there is insufficient data to support a similar conclusion for the ED2-Ø format.

There is evidence of learning effects in the data in that evaluations performed early in the program tended to result in the poorest ratings.

Although crabbing in crosswind approaches considerably eases the control task, there may have been a reluctance, when pilot experience was low, to follow the display commands to headings substantially different from the approach course. As a result the pilot tended to disbelieve the display and attempted to sideslip to align the aircraft heading with the approach course which produced severe control difficulties.

With respect to the flight director display configurations, ED2-2 and AV8-6 evaluated with the AVSAS, repeatability is not at question but rather the marked pilot preference for the ED display format. The single headwind evaluation of ED2-2 received a rating of 1.5 while the ratings for AV8-6 ranged from 4 to 6. The purpose of examining the ratings and comments for these configurations in the context of actual ambient wind conditions was to determine whether factors similar to those which influenced the evaluations previously discussed, also played a part on the evaluations of these configurations. Table 8-2 summarizes the ambient conditions for these evaluations.

TABLE 8-2

AMBIENT WINDS AND TURBULENCE FOR EVALUATIONS OF ED2-2 AND AV8-6 DISPLAYS WITH AVSAS

Display	Headwind (ft/sec)	Turbulence (ft/sec)	Crosswind (ft/sec)	Turbulence (ft/sec)	Flt.	PR
ED2-2	18.4	2.5	-7.1	2.2	178	1.5A
AV8-6	18.1	3.7	16.0	3.4	165	5.5C
	10.9	2.5	4.3	2.6	166	4B
	12.3	3.3	-6.9	3.1	179	6C

It can be seen from the table that with the exception of Flight 165, which was flown in a high crosswind, the ambient conditions are reasonably similar. The comments for this evaluation (AV8-6, PR = 5.5C) indicate that the pilot was crosscontrolled (sideslipping) through the transition and that the display did not make sense. This latter comment is not surprising since the

lateral flight director command contains both lateral error and bank angle and was designed for wings level crabbed approaches in crosswinds when the turn following directional control system (ATC) is selected. Attempting to sideslip wing down results in lateral standoff errors which likely evoked the comment regarding the display not making sense. This evaluation should be excluded from the experiment matrix since it represents either a failure on the part of the experiment designers to brief the evaluation pilot or a memory lapse by the pilot with respect to the proper technique for crosswind approaches with flight director displays.

The evaluation of AV8-6 on Flight 166 (PR = 4B) was flown in the lowest crosswind and turbulence in this group and is considered representative of the best rating to be achieved by this control display combination under good atmospheric conditions. The pilot comments indicate that he anticipated the requirement to change crab angle as he transitioned and had no particular problem tracking the approach course. The major reasons for the less than satisfactory rating are related to flight director jittering and apparent pitch-throttle coupling leading to height control problems as discussed in Section 8.2.

On Flight 179, the AV8-6 configuration was rated PR = 6C. For this evaluation the pilot complained of a tendency to "lose heading and get the ball out." Since crosscontrolling was not mentioned, it is likely that this comment relates to the vehicles lack of directional stiffness. The pilot also compared this display unfavorably to the ED2-2 flight director he had evaluated on the previous flight (F-178, PR = 1.5A), that is, the ED2-2 format in this group. As can be seen from Table 8-2, both evaluations were conducted under similar ambient wind conditions.

The pilot rating data and commentary indicate that under ideal ambient conditions the ED2-2 flight director format is clearly Level 1 while the AV8-6 format has several objectionable deficiencies which preclude a better than acceptable rating. There is insufficient data to assess the sensitivity of pilot rating with the ED2-2 display to the severity of winds and turbulence.

8.3.2 SCAS Authority Limiting

Since the AV8-B employs a mechanical flight control system with limited authority series servos in each of the three control axes for augmentation of vehicle dynamics, it was questionable whether highly augmented control systems could be implemented without excessive saturation of the SCAS actuator authority. Evaluation of the tradeoff between level of augmentation and SCAS authority requirements was performed in this experiment by implementing a simplified representation of the AV-8B flight control system with a variable limit series servo link in the flight control system. Initial evaluations were conducted with no simulated authority limits to establish trends of actuator activity with control system configuration, and to determine baseline flying qualities characteristics uncontaminated by the effects of control system saturation. Following these preliminary flights, authority limits equivalent to twice the AV-8B limits and equal to the AV-8B limits were implemented for the remainder of the program. In terms of equivalent inches of cockpit control displacement, the authority limits of the AV8-B flight control system are:

Pitch:	±0.85 inches	(±1.5 deg elevon)
Roll:	±0.59 inches	(±2.0 deg aileron)
Yaw:	±0.71 inches	(±5.0 deg rudder)

Time histories of simulated SCAS activity were examined for all the evaluations conducted in this program. Pitch SCAS actuator limiting was encountered on only three evaluations as tabulated below:

Flight No.	Control/Display	SCAS Limit	PR
177	2.0 RCAH/AV8-5	AV-8B	3A
180	1.0 ACAH/ED2-2	AV-8B	2.5C
181	2.0 ACAH/AV8-5	AV-8B	7.5D

The limiting encountered on the evaluations of Flights 177 and 180 was momentary and infrequent during the transition. Both the pilot ratings and commentary indicate that the effects of the control limiting had insignificant impact on the task. On Flight 181, the pitch SCAS actuator was almost continuously saturated during the transition. Since this evaluation was conducted in the highest tailwinds encountered in this program (greater than 20 ft/sec) the occurrence of limiting in this case should be considered atypical compared to a more favorable wind situation because tailwinds increase the nose up pitching moment required to decelerate. Based on these data, it is clear that the authorities of the current AV-8B SCAS are sufficient for the levels of augmentation and the approach profiles considered in this experiment.

8.3.3 Control Sensitivity Effects

For all but the AVSAS configuration, control gearing gains were initially established at satisfactory values in the sense of MIL-F-83300 (Reference 9) but pitch and roll gains were varied in the course of the program, primarily in response to pilot commentary. The objective of these variations was to remove, to the greatest extent possible, the effect of control sensitivities on the flying qualities results. Although the range of gains examined effectively spans the Level 1 boundaries of MIL-F-83300, the incremental variations were coarse and not sufficiently systematic to define optimum gains.

The following subsections summarize the gain variations examined for the primary experiment matrix (headwind evaluations), Figure 8.1, and based on pilot commentary assess the impact of these gains on the overall flying qualities. As will be shown, differences in the sensitivity of displayed pitch attitude between the AV8 and ED2 formats were often attributed to the control system. Pilot commentary, therefore, must be used with caution and must be considered in the context of the overall system (control and display configuration).

• 1.0 RCAH - Pitch Control Sensitivity

For this configuration, pitch damping was 2.2 sec^{-1} and only a single value of control sensitivity was simulated ($M_{\delta_{ES}}$ = 0.23 rad/sec^2/in.). On two of these evaluations, display sensitivity differences were attributed to the control system.

Flight 163, AV8-5, PR = 5A: "sensitivity too high in pitch"

Flight 178, ED2-Ø, PR = 3C: "would like a little more sensitivity to handle middle part of transition.....mildly unpleasant deficiency in pitch response in transition."

Taken in the context of the pilots overall commentary, the observed pitch control sensitivity deficiencies are minor in nature and it is concluded that for this configuration, the control gearing was satisfactory and had little or no influence on the pilot rating.

• 2.0 RCAH - Pitch Control Sensitivity

The effective pitch damping for this configuration was 3.6 sec^{-1} and control sensitivities from 0.23 to 0.78 rad/sec^2/in. were examined. Pilot ratings for this group ranged from PR = 2.5 at the lowest sensitivity to PR = 4 at the highest. Pilot comments for $M_{\delta_{ES}}$ = 0.23 rad/sec^2/in. indicate a need for more sensitivity while excessive sensitivity is cited for $M_{\delta_{ES}}$ = 0.78 rad/sec^2/in. Based on the total spread in pilot ratings it would appear that a broad range of sensitivity can be accommodated by the pilot but that the optimum likely lies near the intermediate sensitivity evaluated ($M_{\delta_{ES}}$ = 0.43 rad/sec^2/in.). Pitch control sensitivity was not a dominant factor in this group of evaluations.

• RCAH - Roll Control Sensitivity

The augmentation of the roll axis was identical for each of the pitch configurations. The effective damping in roll was 3.2 sec^{-1} with control sensitivities varied from .62 to 1.80 rad/sec^2/in. As in pitch, a wide variation in control sensitivities can be tolerated since the ratings for this group ranged from PR = 2.5 to PR = 5. Every configuration evaluated

with high control gearing ($L'_{\delta_{AS}}$ = 1.54 and 1.80 rad/sec^2/in.) elicited comments about excessive sensitivity but with one exception, pilot ratings were not seriously degraded.

Flight 158, $L'_{\delta_{AS}}$ = 1.54, PR = 2.5
Flight 162, $L'_{\delta_{AS}}$ = 1.80, PR = 3
Flight 163, $L'_{\delta_{AS}}$ = 1.80, PR = 5

The optimum control sensitivity likely lies in the region of the lower gains evaluated, i.e., $L'_{\delta_{AS}}$ from 0.62 to 0.99 rad/sec^2/in.

- 1.0 ACAH - Pitch Control Sensitivity

Only one control sensitivity was simulated for this dynamic configuration ($M_{\delta_{ES}}$ = 0.23 rad/sec^2/in.). Pilot ratings varied from PR = 2.5 to PR = 4. As in the RCAH configurations, this group also showed evidence of control and display sensitivity interaction. For example:

Flight 167, AV8-5, PR = 4B: "pitch attitude sensitive.....tendency to overcontrol in hover"
Flight 168, ED2-Ø, PR = 4A: "pitch sensitivity too low"

Clearly, the pilot's perception of vehicle control response, in these cases, is based on what he sees; proprioceptive and vestibular cues are too insensitive to allow him to distinguish actual from apparent vehicle motion. Based on the small variation in ratings for all these configurations, the pitch response sensitivity complaints are minor deficiencies and had little impact on the pilot rating.

- 1.5 ACAH - Pitch Control Sensitivity

Three evaluations of this control configuration were performed with pitch control sensitivity held constant at 0.23 rad/sec^2/in. With both the AV8 and ED2 display formats the pitch control response was described as good. Since the ratings for this group ranged from PR = 3 to PR = 4, the overall control/display response for both display formats were satisfactory and were not detrimental to the pilot rating.

- 2.0 ACAH - Pitch Control Sensitivity

Only one evaluation of this configuration was performed under headwind conditions with the ED2-Ø display format. Pitch control sensitivity was high ($M_{\delta_{ES}}$ = 0.78 rad/sec^2/in.) and the pilot complained of abrupt pitch response (and roll response as will be discussed in the next section). Control difficulties in both axes dominate the comments and likely account for the degraded pilot rating (PR = 5A). Extrapolating from the data of Figure 8.1 with the control sensitivity reduced, this configuration would probably exhibit Level 1 flying qualities (PR $\leq$ 3.5).

- ACAH - Roll Control Sensitivities

All the pitch attitude command configurations were evaluated with one level of augmentation in roll (ω_n = 2.2 rad/sec). Control gearings in the roll axis were varied from 0.5 to 1.80 rad/sec^2/in. For the single evaluation of the lowest roll control gearing (1.0 ACAH, ED2-2) on Flight 165, the roll control gearing was too low and in the pilots estimation degraded the rating from a PR = 2 to PR = 4. For the highest gearing ($L_{\delta_{AS}}$ = 1.80 rad/sec^2/in.) the pilots consistently complained of high control sensitivity although the ratings, which varied from PR = 2.5 to 4, do not reflect serious flying qualities deficiencies. At intermediate control sensitivities, ($L_{\delta_{AS}}$ = 1.38 and 1.54 rad/sec^2/in.) roll control response was judged satisfactory with one exception (2.0 ACAH discussed above); the ratings in this group varied from PR = 3 to PR = 4. No serious degradation in flying qualities appears to have been introduced through any of the roll gearings employed for the attitude command configurations.

In summary, although a wide range of control gearings were examined for selected configurations in this experiment, the pilot rating data, in general, reflect little sensitivity to this parameter. Of the data presented in Figure 8.1, it is considered that the ratings for the following evaluations may have been degraded by the magnitude of the control sensitivities.

Flight 165, ED2-2, 1.0 ACAH - roll sensitivity low

Flight 168, ED2-Ø, 2.0 ACAH - pitch and roll sensitivity high

Flight 163, AV8-5, 1.0 RCAH - roll sensitivity high

Flight 166, AV8-6, 1.0 ACAH - roll sensitivity high

Section 9

CONCLUSIONS AND RECOMMENDATIONS

The flight experiment described in this report was conducted using the X-22A V/STOL aircraft, which is capable of varying stability characteristics, control augmentation systems and display presentations in flight. In this case, the aerodynamic characteristics simulated and the approach profiles flown were representative of a jet-lift VTOL aircraft, the AV-8B Advanced Harrier. Furthermore, the control systems investigated were predicated on a particular form of implementation, that is, a limited authority series actuator link in each axis of the mechanical flight control system. Hence, the dynamic situations investigated were constrained to those typical of Harrier-class VTOL aircraft. In this context, the following general conclusions may be drawn:

- The X-22A aircraft provided a simulation of the AV-8B of sufficient validity for the conduct of this control/display investigation.

- It is possible to provide control/display combinations within the proposed AV-8B capabilities, as simulated in this experiment, that permit instrument approaches with a final deceleration from 65 kt to hover.

The pilot rating and comment data were obtained from a single evaluation pilot; these data together with measured ambient winds and turbulence and control usage lead to the following conclusions pertinent to the control system and display variations investigated in this experiment.

- Primarily because of the absence of explicit position information relative to the landing pad, the proposed AV-8B HUD format (AV8-Ø in this experiment) will not provide a satisfactory system (PR $\leqslant$ 3.5) for the full instrument approach to hover regardless of control augmentation.

- Even with a breakout to visual conditions (approximately 800 feet range, 100 feet AGL) the combination of the basic AV-8B SAS (AVSAS) and AV-8B HUD format needs improvement.

- Pilot ratings with the proposed AV-8B rate-damper control system are sensitive to display information nuances, environmental variations (crosswind and turbulence magnitude) and pilot technique. Except under ideal conditions, satisfactory instrument approaches will be very difficult to obtain with this control system regardless of displayed information.

- The addition of attitude stabilization, in either rate command with attitude hold (such as proposed for the AV-8B) or attitude command control mechanizations provides satisfactory instrument approach to hover capability for all but the basic AV-8B display format (AV8-Ø).

- Although not evident in the pilot rating data, pilot commentary indicates a clear preference for the ED2 display format. A major complaint with the AV8 display was the difficulty of perceiving pitch and bank attitudes via the pitch ladder. Using the chevrons to mark the approach attitude tended to ameliorate this problem.

- Differences in display sensitivity (i.e., symbol displacement per unit state variable change) can be interpreted by the pilot as differences in control sensitivity. In particular, with the AV8 display formats (3:1 pitch ladder scaling), vehicle pitch control sensitivity was often described as high while

the converse was observed with the ED2 formats (16:1 horizon line scaling). A fruitful area for future research is the investigation of the interaction of display scaling and vehicle response dynamics for optimum manual control of the approach trajectory.

- For the approach profile flown, the SCAS authorities of the current AV-8B flight control system are adequate for any of the control system concepts considered in this experiment; SCAS actuator limiting was not a significant factor in any of the approaches flown in the absence of tailwinds and with reasonable control sensitivities.

- The rank ordering of the various display formats and control system concepts is not evident in the pilot rating data of this experiment to the extent seen in the previous X-22A investigation (Reference 2). This difference may be attributable to the concentration on rate and attitude control systems coupled with less marked information differences among the displays.

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GLOSSARY OF SYMBOLS AND ABBREVIATIONS

Symbol

Symbol	Definition
A	eigenvector matrix
a_X, a_Y, a_Z	acceleration along body X, Y, Z axis respectively (ft/sec^2)
F	equations-of-motion characteristic matrix (1/sec)
F_{ES}	longitudinal stick force (lb)
F_{AS}	lateral stick force (lb)
g	acceleration due to gravity (32.2 ft/sec^2)
G	equations-of-motion control matrix
h	altitude (ft)
HBAR	horizontal bar control director deflection (volts)
$I_{(\ )}$	moment of inertia about body ( )-axis (ft-lb/sec^2)
I_{XZ}	product of inertia in body axes (ft-lb/sec^2)
K	linear gain; state feedback gain matrix (Section V)
$K_{(\ )}$	control director gain (volts/( ))
K_d	display position constant (cm)
K_L	non-dimensional inertia coupling in roll $\left(= \frac{I_Y - I_Z}{I_X}\right)$
K_N	non-dimensional inertia coupling in yaw $\left(= \frac{I_X - I_Y}{I_Z}\right)$
K_r	lateral guidance gain (deg/ft)
K_1, K_2	complementary filter gains
L	aerodynamic moment about body X-axis (ft-lb)
$L'_{(\ )}$	dimensional rolling moment derivative $= \frac{1}{I_X}\left(1 - I_{XZ}^2 / I_X I_Z\right)^{-1}\left[\frac{\partial L}{\partial(\ )} + \frac{I_{XZ}}{I_X}\frac{\partial N}{\partial(\ )}\right] \quad \left(\frac{\text{rad/sec}^2}{(\ )}\right)$
M	aerodynamic moment about body Y-axis (ft-lb)
$M_{(\ )}$	dimensional pitching moment derivative $= \frac{1}{I_Y}\frac{\partial M}{\partial(\ )} \quad \left(\frac{\text{rad/sec}^2}{(\ )}\right)$
n_y, n_z	acceleration along body X and Y axes, respectively (g's)
N	aerodynamic moment about body Z-axis (ft-lb)

GLOSSARY OF SYMBOLS AND ABBREVIATIONS (Cont.)

Symbol	
$N'_{(\ )}$	dimensional yawing moment derivative $= \frac{1}{I_x}\left(1 - I_{xz}^2 / I_x I_z\right)^{-1}\left[\frac{\partial L}{\partial(\ )} + \frac{I_{xz}}{I_x}\frac{\partial N}{\partial(\ )}\right] \left(\frac{\text{rad/sec}^2}{(\ )}\right)$
p	body axis roll rate (deg/sec, rad/sec)
P	steady-state augmented control gain matrix (Section V)
q	body axis pitch rate (deg/sec, rad/sec)
Q	optimal control state weighting matrix (Section III)
r	body axis yaw rate (deg/sec, rad/sec)
R	optimal control weighting matrix (Section III)
s	Laplace operator $\sigma \pm j\omega$
t	time (sec)
u	velocity along body X-axis (ft/sec)
v	velocity along body Y-axis (ft/sec)
V	velocity (ft/sec, kt)
V_e	horizontal inertial velocity vector (ft/sec)
V_w	horizontal wind velocity vector (ft/sec)
$V_{w_{(\ )}}$	wind velocity component in ( ) direction (ft/sec)
VBAR	vertical bar control director deflection (volts)
VTAB	vertical tab control director deflection (volts)
w	velocity along body Z-axis (ft/sec)
X, Y, Z	generalized position coordinates (ft)
$X_{(\ )}, Y_{(\ )}, Z_{(\ )}$	dimensional longitudinal, lateral, and vertical force derivatives $= \frac{1}{M}\frac{\partial X, Y, \text{ or } Z}{\partial(\ )} \left(\frac{\text{ft/sec}^2}{(\ )}\right)$
X	position (Section VI) (ft)
Z_Y	height of accelerometer package above aircraft center of gravity (ft)
α	angle of attack (deg, rad)
β	angle of sideslip (deg, rad)
γ	flight path angle (deg)

GLOSSARY OF SYMBOLS AND ABBREVIATIONS (Cont.)

Symbol

Γ course (deg)

$\delta_{(\ )}$ evaluation pilot's controller position

- AS - lateral stick (in)
- ES - longitudinal stick (in)
- RP - rudder pedal (in)
- T - throttle lever stick (in)
- θ_j - thrust vector angle (deg)

$\Delta(\ )$ perturbation term $(\ )-(\ )_o$, units of ( )

$\Delta_{(\ )}$ safety pilot's controller position

- as - lateral stick (in)
- es - longitudinal stick (in)
- cs - collective stick (deg)
- rp - rudder pedal (in)

$\epsilon(\ )$ error term = $(\ )_c - (\ )$, units of ( )

ζ damping ratio

ζ_d damping ratio of Dutch roll characteristic roots

θ pitch attitude (deg, rad)

$\Lambda_{(\ )}$ eigenvalue matrix

- P - plant
- m - model

λ X-22A duct angle measured from horizontal (deg)

σ real portion of Laplace operator

τ generalized time constant (sec)

τ_R roll mode time constant (sec)

τ_s spiral mode time constant (sec)

ϕ roll angle (deg, rad)

ψ heading angle $\triangleq \psi_N - \psi_A$ (deg)

ψ_A approach course heading with respect to North (deg)

ψ_N aircraft heading with respect to North (deg)

GLOSSARY OF SYMBOLS AND ABBREVIATIONS (Cont.)

Symbols

ω	generalized angular frequency imaginary portion of Laplace operator (rad/sec)
ω_n	undamped natural frequency (rad/sec)
ω_d	undamped natural frequency of Dutch roll mode (rad/sec)
ω_ϕ	undamped natural frequency of numerator roots in ϕ/δ_{as} transfer function (rad/sec)
$(\dot{\ })$	time rate of change of ( ), ( )/sec
$(\hat{\ })$	estimate of ( ), units of ( )
$(\ )_{AS}$, $(\ )_{BS}$	"after-switching" and "before switching" values of ( ) respectively, units of ( )
$(\ )_{WO}$	washed-out value of ( ), units of ( )
$(\ )_{o}$	initial or trim value of ( ), units of ( )

Abbreviation

ACAH	attitude command/attitude hold
ADI	attitude director indicator
AGARD	Advisory Group for Aerospace Research and Development
AGL	above ground level
ANOVA	analysis of variance
ARI	aileron-rudder interconnect
ATC	automatic turn coordination
CRT	cathode ray tube
CTOL	conventional take-off and landing
DAC	digital-to-analog converter
dB	decibel
deg	degrees
DME	distance measuring equipment
ED	electronic display
F-( )	flight number ( )
FFCS	Feedforward Flight Control System
fpm	feet per minute

GLOSSARY OF SYMBOLS AND ABBREVIATIONS (Cont.)

Abbreviation	
ft	feet
GS	glide slope
HDD	head down display
HH	heading hold
Hz	Hertz
IAS	indicated airspeed
ILS	Instrument Landing System
IMC	Instrument Meteorological Conditions
in	inches
ITVIC	Independent Thrust Vector Inclination Command
IVSI	Instantaneous Vertical Speed Indicator
KIAS	knots indicated airspeed
Kt	Knots
LOC	localizer
LORAS	Linear Omnidirectional Resolving Airspeed System
MCAIR	McDonnell-Douglas Aircraft Corporation
MLS	Microwave Landing System
NASA	National Aeronautics and Space Administration
PDU	pilot display unit
PR	Cooper-Harper pilot rating
RCAH	rate command/attitude hold
rad	radian
SCAS	stability and control autmentation system
sec	second
STOL	short takeoff and landing
TER	turbulence effect rating
VALT	VTOL Approach and Landing Technology
VBAR	vertical bar control director
VMC	Visual Meteorological Conditions
VSS	variable stability system

GLOSSARY OF SYMBOLS AND ABBREVIATIONS (Cont.)

Abbreviation	
V/STOL	vertical/short takeoff and landing
VTAB	vertical tab control director
VTOL	vertical takeoff and landing
YRC/HH	yaw rate command/heading hold

APPENDIX I
MASTER DATA SUMMARY

This appendix contains data and background information pertinent to the technical discussion and results presented in this report. The following paragraphs describe the contents of this appendix.

Table I-1 is the run log summarizing the display and augmentation system configurations evaluated in this experiment grouped according to flight control system and display configuration. Also tabulated are the pitch and roll control sensitivities (rad/sec^2/in.) employed since selected dynamic configurations were evaluated with a range of pitch and roll control gearings. As described in Section 7, for each configuration, the pilot was asked to assign an initial "quick look" pilot rating, a final rating following comments, an estimated rating with the hover excluded, and a turbulence effect rating. These data are tabulated as: initial rating/final rating/rating with hover excluded, turbulence rating.

Table I-2 presents the transfer characteristics for the augmented AV-8B configurations using the notation $K(s+\lambda)(s^2 + 2\zeta\omega_n s + \omega_n^2) \Rightarrow K(\lambda)[\zeta; \omega_n]$. The transfer function gains (control sensitivities) are those of the AV-8B. For configurations with control gearings different from the AV-8B, the appropriate ratio should be applied to the gains of Table I-2.

Table I-3 is a summary of the open loop transfer functions of the flight director commands to control displacement.

Figures I-1 and I-2 depict the scaling functions for the HUD displacement error signal and the landing pad size.

Figures I-3 and I-4 present time histories of longitudinal and lateral directional responses to control inputs comparing the AV-8B linear model and the X-22A simulation of the AV-8B.

Figures I-5, I-6 and I-7 illustrate the open loop frequency responses of the flight director command symbols (HBAR, VTAB, VBAR) to their respective controllers (δ_{ES} , δ_T , δ_{AS}). It is noted that the phase of the HBAR and VTAB transfer functions approach -270 degrees at high frequency rather than -90 degrees as would be expected for K/S behavior. The additional 180 degrees of phase is attributable to the sign convention used for positive symbol displacement on the HUD. In the case of HBAR and VTAB, positive displacement of the pitch stick and throttle lever produces negative displacement of the flight director symbol.

TABLE I-1

SUMMARY OF CONFIGURATIONS EVALUATED

CONTROL SYSTEM	DISPLAY CONFIG	FLT #	CONTROL SENS (rad/sec^2/in) PITCH	ROLL	SAS AUTH LIMIT	PILOT RATING	TURB RATING
AVSAS	AV8-Ø	158	0.23	0.50	UNLIM	7/7/4	
		167	"	"	AV-8B	5/5/4	C
		178	"	"	"	5/5/-	C
	AV8-3	165	"	"	"	6/6/-	D
	AV8-5	162	"	"	UNLIM	5.5/5.5/5.5	
		163	"	"	AV-8B	7/7/4.5	A
		179	"	"	"	2.5/2.5/2.5	C
		181	"	"	"	-/4.5/4.5	D
	AV8-6	165	"	"	"	5/5.5/5.5	C
		166	"	"	"	4/4/4	B
		179	"	"	"	-/6/4.5	C
	ED2-Ø	167	"	"	"	3/3/3	B
		177	"	"	"	-/3/3	A
		181	"	"	"	6/7/6	D
	ED2-1	166	"	"	"	5/5/5	B
		178	"	"	"	-/5.5/4.5	C
	ED2-2	164	"	"	"	7/7/7	A
		178	"	"	"	1.5/1.5/1.5	A
		181	"	"	"	5/5/5	C
RCAH 1.0	AV8-5	160	"	1.80	UNLIM	5/5/5	
		162	"	"	"	3/3/3	
		163	"	"	AV-8B	5/5/5	A
	ED2-Ø	164	"	0.99	"	6/6/4.5	D
		178	"	0.62	"	-/3/3	C
RCAH 2.0	AV8-3	169	0.33	0.88	UNLIM	3/-/-	
	AV8-5	158	0.23	1.54	"	3/2.5/-	
		177	0.33	0.99	AV-8B	3/3/3	A
	ED2-Ø	168	0.78	"	2xAV-8B	4/4/4	A
		168	0.23	"	"	3/3/2.5	C

AD-A068 818 CALSPAN CORP BUFFALO N Y F/G 1/3
AN EXPERIMENTAL INVESTIGATION OF CONTROL-DISPLAY REQUIREMENTS F--ETC(U)
JUL 78 J V LEBACQZ, R C RADFORD, J L BEILMAN N62269-76-C-0370
UNCLASSIFIED CALSPAN-AK-5985-F-1 NADC-76099-60 NL

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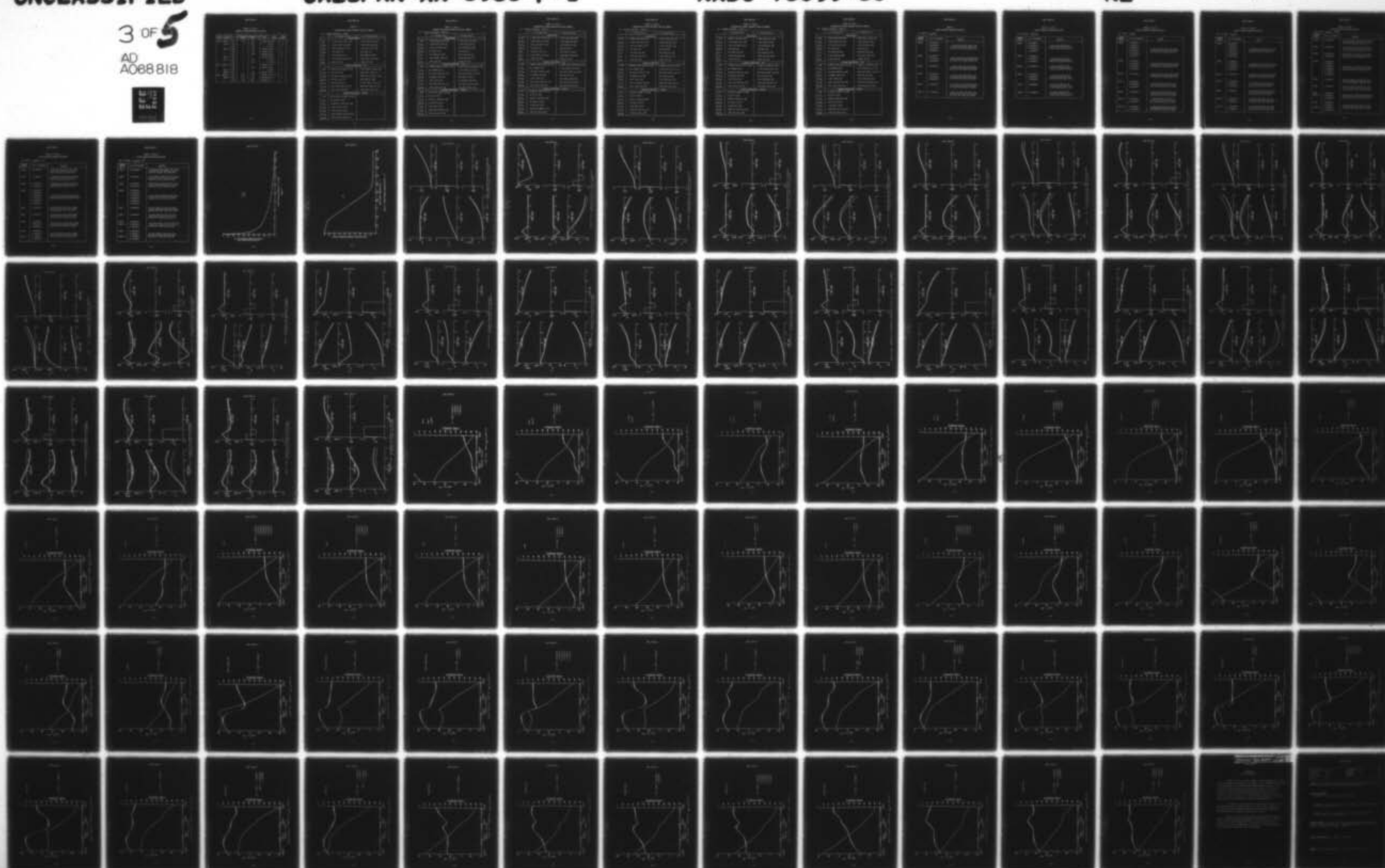

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1.0 1.1 1.25 1.4 1.6 1.8 2.0 2.2 2.5 2.8 3.2 3.6 4.0 4.5 5.0 5.6 6.3

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

TABLE I-1 (Cont.)

SUMMARY OF CONFIGURATIONS EVALUATED

CONTROL SYSTEM	DISPLAY CONFIG	FLT #	CONTROL SENS ($rad/sec^2/in$) PITCH	ROLL	SAS AUTH LIMIT	PILOT RATING	TURB RATING
ACAH 1.0	AV8-5	167	0.23	1.38	AV-8B	4/4/2.5	B
	AV8-6	164	"	0.50	"	4/4/4	B
		166	"	1.80	"	4/4/4	C
	ED2-Ø	158	"	1.54	UNLIM	3/3/3	
		163	"	1.80	AV-8B	3/3/3	A
		168	"	1.38	2xAV-8B	4/4/2	A
	ED2-1	181	"	"	AV-8B	6/6/6	D
	ED2-2	165	"	0.50	"	4/4/4	
		180	"	1.80	"	-/2.5/1.5	C
ACAH 1.5	AV8-Ø	160	"	"	UNLIM	7/7/3	
		179	"	1.38	AV-8B	-/3/-	C
	AV8-3	179	"	"	"	4/4/4	C
	ED2-Ø	162	"	1.80	UNLIM	4/4/4	
ACAH 2.0	AV8-5	181	0.33	1.38	AV-8B	7.5/7.5/7	D
	ED2-Ø	168	0.78	1.38	2xAV-8B	5/5/4	A
		169	0.33	0.88	UNLIM	5/-/-	

TABLE I-2

AUGMENTATION SYSTEM TRANSFER FUNCTION SUMMARY

(a) Transfer Functions - AVSAS

	λ = 90 deg (0 Kt)	λ = 50 deg (65 Kt)
	LONGITUDINAL	
$\Delta(S)$	(-.035)(.040)(.15)(3.76)	(-.14)(.18)(.49)(4.11)
N_u/δ_{ES}	-.161(.012)[-.01;6.78]	-.139(.25)[.34;9.36]
N_w/δ_{ES}	-.35(.11)(1.06)(-1.05)	-.33(-79.9) [.39;.28]
N_θ/δ_{ES}	.23(.012)(.14)	.24(.063)(.52)
N_u/δ_c	.34(2.15)(.96;.70)	.225(.18)[.79;3.92]
N_w/δ_c	-2.55(.0016)(.149)(3.83)	-2.26(.051)(.17)(5.89)
N_θ/δ_c	-.036(.14)(.32)	-.036(.17)(.56)
	LATERAL-DIRECTIONAL - ATC	
$\Delta(S)$	(.022)(.74)(3.07)[.32;.16]	(.021)(.49)(3.77)[.40;76]
N_v/δ_{AS}	16.1(.019)(.73)	-8.65(.12)(-.56)(1.73)
N_r/δ_{AS}	.03(.32)(-1.04)[.54;1.12]	.0955(.32)(2.53)[.11;.66]
N_ϕ/δ_{AS}	.5(.019)(.12)(.73)	.480(.32)[.52;.89]
N_v/δ_{RP}	-1.93(-.014)(.32)	-27.56(-.020)(.32)(3.87)
N_r/δ_{RP}	.225(.32)(3.13)[.33;.17]	.248(.32)(3.84)[.32;.41]
N_ϕ/δ_{RP}	-.06(-.014)(.12)(.32)	-.08(.32)(2.43)(-2.96)
	LATERAL-DIRECTIONAL - YRC/HH	
$\Delta(S)$	(0)(3.04)[.33;.18][.77;1.07]	
N_v/δ_{AS}	16.1(0)[.77;1.07]	
N_r/δ_{AS}	.03(0)(0)(-1.18)[.53;1.26]	
N_ϕ/δ_{AS}	.5(0)(.12)[.77;1.07]	
N_v/δ_{RP}	-1.93(1.0)(0)(.0143)	
N_r/δ_{RP}	.225(1.0)(0)(3.13)[.33;.17]	
N_ϕ/δ_{RP}	-.06(1.0)(0)(-.014)(.12)	

TABLE I-2 (Cont.)

AUGMENTATION SYSTEM TRANSFER FUNCTION SUMMARY

(b) Transfer Functions - RCAH 1.0

	λ = 90 deg (0 Kt)	λ = 50 deg (65 Kt)
LONGITUDINAL		
$\Delta(S)$	(-.048)(.048)(.16)(2.18)	(-.20)(.22)(.47)(2.49)
N_u/δ_{ES}	-.161(.012)[-.01;6.78]	-.139(.25)[.34;9.36]
N_w/δ_{ES}	-.35(.11)(1.06)(-1.05)	-.33(-79.9)[.39;.28]
N_θ/δ_{ES}	.23(.012)(.14)	.24(.063)(.52)
N_u/δ_c	.34(-.39)[.49;1.66]	.225(.23)[.67;3.46]
N_w/δ_c	-2.55(.0028)(.15)(2.21)	-2.26(4.20)[.99;.11]
N_θ/δ_c	-.036(.14)(.32)	-.036(.17)(.56)
LATERAL-DIRECTIONAL - ATC		
$\Delta(S)$	(.0059)(1.98)(3.20)[.34;.17]	(-.0045)(.53)(3.92)[.69;1.41]
N_v/δ_{AS}	16.1(.0069)(1.95)	-1.707(.023)(1.57)(13.5)
N_r/δ_{AS}	.03(.32)(1.30)[.47;1.22]	.033(.32)(1.95)[-.44;2.21]
N_ϕ/δ_{AS}	.5(.0069)(.12)(1.95)	.50(.33)[.76;1.46]
N_v/δ_{RP}	-1.93(-.014)(.32)	-2.76(.019)(.32)(4.05)
N_r/δ_{RP}	.225(.32)(3.31)[.34;.17]	.248(.32)(4.02)[.33;.40]
N_ϕ/δ_{RP}	-.06(-.014)(.12)(.32)	-.08(.32)(2.43)(-2.96)
LATERAL-DIRECTIONAL - YRC/HH		
$\Delta(S)$	(3.22)[.34;.17][.77;1.07]	
N_v/δ_{AS}	16.1[.77;1.07]	
N_r/δ_{AS}	.03(0)(-1.18)[.53;1.26]	
N_ϕ/δ_{AS}	.5(.12)[.77;1.07]	
N_v/δ_{RP}	-1.93(1.0)(-.014)	
N_r/δ_{RP}	.225(1.0)(3.31)[.34;.17]	
N_ϕ/δ_{RP}	-.06(1.0)(.12)(-.014)	

TABLE I-2 (Cont.)

AUGMENTATION SYSTEM TRANSFER FUNCTION SUMMARY

(c) Transfer Functions - RCAH 2.0

	λ = 90 deg (0 Kt)	λ = 50 deg (65 Kt)
LONGITUDINAL		
△(S)	(-.036)(.041)(.15)(3.55)	(-.15)(.18)(.49)(3.89)
N_u/δ_{ES}	-.161(.012)[-.01;6.78]	-.139(.25)[.34;9.36]
N_w/δ_{ES}	-.35(.11)(1.06)(-1.05)	-.33(-79.9)[.39;.28]
N_θ/δ_{ES}	.23(.012)(.14)	.24(.063)(.52)
N_u/δ_c	.34(.60)(1.13)(1.57)	.225(.18)[.77;3.86]
N_w/δ_c	-2.55(.0017)(.15)(3.61)	-2.26(.054)(.16)(5.66)
N_θ/δ_c	-.036(.14)(.32)	-.036(.17)(.56)
LATERAL-DIRECTIONAL - ATC		
△(S)	(.0059)(1.98)(3.20)[.34;.17]	(-.0045)(.53)(3.92)[.69;1.41]
N_v/δ_{AS}	16.1(.0069)(1.95)	-1.707(.023)(1.57)(13.5)
N_r/δ_{AS}	.03(.32)(1.30[.47;1.22]	.033(.32)(1.95)[-.44;2.21]
N_ϕ/δ_{AS}	.5(.0069)(.12)(1.95)	.50(.33)[.76;1.46]
N_v/δ_{RP}	-1.93(-.014)(.32)	-2.76(.019)(.32)(4.05)
N_r/δ_{RP}	.225(.32)(3.31)[.34;.17]	.248(.32)(4.02)[.33;.40]
N_ϕ/δ_{RP}	-.06(-.014)(.12)(.32)	-.08(.32)(2.43)(-2.96)
LATERAL-DIRECTIONAL - YRC/HH		
△(S)	(3.22)[.34;.17][.77;1.07]	
N_v/δ_{AS}	16.1[.77;1.07]	
N_r/δ_{AS}	.03(0)(-1.18)[.53;1.26]	
N_ϕ/δ_{AS}	.5(.12)[.77;1.07]	
N_v/δ_{RP}	-1.93(1.0)(-.014)	
N_r/δ_{RP}	.225(1.0)(3.31)[.34;.17]	
N_ϕ/δ_{RP}	-.06(1.0)(.12)(-.014)	

TABLE I-2 (Cont.)

AUGMENTATION SYSTEM TRANSFER FUNCTION SUMMARY

(d) Transfer Functions - ACAH 1.0

	λ = 90 deg (0 Kt)	λ = 50 deg (65 Kt)
LONGITUDINAL		
$\Delta(S)$	(.0062)(.14)(.66)(1.53)	(-.031)(1.99)[.96;.53]
N_u/δ_{ES}	-.161(.012)[-.01;6.78]	-.139(.25)[.34;9.36]
N_w/δ_{ES}	-.35(.11)(1.06)(-1.05)	-.33(-79.9)[.39;.28]
N_θ/δ_{ES}	.23(.012)(.14)	.24(.063)(.52)
N_u/δ_c	.34(.28)[.45;1.96]	.225(.39)[.64;3.50]
N_w/δ_c	-2.55(.14)(.67)(1.55)	-2.26(3.93)[.91;.27]
N_θ/δ_c	-.036(.14)(.32)	-.036(.17)(.56)
LATERAL-DIRECTIONAL - ATC		
$\Delta(S)$	(.0068)(.15)(1.92)[.72;2.24]	(.28)[.67;1.75][.93;2.02]
N_v/δ_{AS}	16.1(.0069)(1.95)	-1.707(.023)(1.57)(-13.5)
N_r/δ_{AS}	.03(.32)(1.30)[.47;1.22]	.033(.32)(1.95)[-.44;2.21]
N_ϕ/δ_{AS}	.5(.0069)(.12)(1.95)	.50(.33)[.76;1.46]
N_v/δ_{RP}	-1.93(-.014)(.32)	-2.76(.32)[.90;2.23]
N_r/δ_{RP}	.225(.15)(.32)[.73;2.24]	.248(.32)(.47)[.89;2.13]
N_ϕ/δ_{RP}	-.06(-.014)(.12)(.32)	-.08(.32)(2.43)(-2.96)
LATERAL-DIRECTIONAL - YRC/HH		
$\Delta(S)$	(.14)[.72;2.24][.77;1.06]	
N_v/δ_{AS}	16.1[.77;1.07]	
N_r/δ_{AS}	.03(0)(-1.18)[.53;1.26]	
N_ϕ/δ_{AS}	.5(.12)[.77;1.07]	
N_v/δ_{RP}	-1.93(1.0)(-.014)	
N_r/δ_{RP}	.225(1.0)(.15)(.73;2.24)	
N_ϕ/δ_{RP}	-.06(1.0)(.12)(-.014)	

TABLE I-2 (Cont.)

AUGMENTATION SYSTEM TRANSFER FUNCTION SUMMARY

(e) Transfer Functions - ACAH 1.5

	λ = 90 deg (0 Kt)	λ = 50 deg (65 Kt)
LONGITUDINAL		
$\Delta(S)$	(.0090)(.14)[.98;1.44]	(.018)(.58)(.87)(2.19)
N_u/δ_{ES}	-.161(.012)[-.01;6.78]	-.139(.25)[.34;9.36]
N_w/δ_{ES}	-.35(.11)(1.06)(-1.05)	-.33(-79.9)[.39;.28]
N_θ/δ_{ES}	.23(.012)(.14)	.24(.063)(.52)
N_u/δ_c	.34(.22)[.55;2.19]	.225(.51)[.66;3.72]
N_w/δ_c	-2.55(.14)[.98;1.46]	-2.26(.26)(.46)(4.38)
N_θ/δ_c	-.036(.14)(.32)	-.036(.17)(.56)
LATERAL-DIRECTIONAL - ATC		
$\Delta(S)$	(.0068)(.15)(1.92)[.72;2.24]	(.28)[.67;1.75][.93;2.02]
N_v/δ_{AS}	16.1(.0069)(1.95)	-1.707(.023)(1.57)(-13.5)
N_r/δ_{AS}	.03(.32)(1.30)[.47;1.22]	.033(.32)(1.95)[-.44;2.21]
N_ϕ/δ_{AS}	.5(.0069)(.12)(1.95)	.50(.33)[.76;1.46]
N_v/δ_{RP}	-1.93(-.014)(.32)	-2.76(.32)[.90;2.23]
N_r/δ_{RP}	.225(.15)(.32)[.73;2.24]	.248(.32)(.47)[.89;2.13]
N_ϕ/δ_{RP}	-.06(-.014)(.12)(.32)	-.08(.32)(2.43)(-2.96)
LATERAL-DIRECTIONAL - YRC/HH		
$\Delta(S)$	(.14)[.72;2.24][.77;1.06]	
N_v/δ_{AS}	16.1[.77;1.07]	
N_r/δ_{AS}	.03(0)(-1.18)[.53;1.26]	
N_ϕ/δ_{AS}	.5(.12)[.77;1.07]	
N_v/δ_{RP}	-1.93(1.0)(-.014)	
N_r/δ_{RP}	.225(1.0)(.15)(.73;2.24)	
N_ϕ/δ_{RP}	-.06(1.0)(.12)(-.014)	

TABLE I-2 (Cont.)

AUGMENTATION SYSTEM TRANSFER FUNCTION SUMMARY

(f) Transfer Functions - ACAH 2.0

	λ = 90 deg (0 Kt)	λ = 50 deg (65 Kt)
LONGITUDINAL		
$\Delta(S)$	(.010)(.14)[.95;1.86]	(.036)(.54)(1.38)(2.46)
N_u/δ_{ES}	-.161(.012)[-.01;6.78]	-.139(.25)[.34;9.36]
N_w/δ_{ES}	-.35(.11)(1.06)(-1.05)	-.33(-79.9)[.39;.28]
N_θ/δ_{ES}	.23(.012)(.14)	.24(.063)(.52)
N_u/δ_c	.34(.18)[.64;2.46]	.225(.64)[.69;3.96]
N_w/δ_c	-2.55(.14)[.96;1.88]	-2.26(.24)(.73)(4.91)
N_θ/δ_c	-.036(.14)(.32)	-.036(.17)(.56)
LATERAL-DIRECTIONAL - ATC		
$\Delta(S)$	(.0068)(.15)(1.92)[.72;2.24]	(.28)[.67;1.75][.93;2.02]
N_v/δ_{AS}	16.1(.0069)(1.95)	-1.707(.023)(1.57)(-13.5)
N_r/δ_{AS}	.03(.32)(1.30)[.47;1.22]	.033(.32)(1.95)[-.44;2.21]
N_ϕ/δ_{AS}	.5(.0069)(.12)(1.95)	.50(.33)[.76;1.46]
N_v/δ_{RP}	-1.93(-.014)(.32)	-2.76(.32)[.90;2.23]
N_r/δ_{RP}	.225(.15)(.32)[.73;2.24]	.248(.32)(.47)[.89;2.13]
N_ϕ/δ_{RP}	-.06(-.014)(.12)(.32)	-.08(.32)(2.43)(-2.96)
LATERAL-DIRECTIONAL - YRC/HH		
$\Delta(S)$	(.14)[.72;2.24][.77;1.06]	
N_v/δ_{AS}	16.1[.77;1.07]	
N_r/δ_{AS}	.03(0)(-1.18)[.53;1.26]	
N_ϕ/δ_{AS}	.5(.12)[.77;1.07]	
N_v/δ_{RP}	-1.93(1.0)(-.014)	
N_r/δ_{RP}	.225(1.0)(.15)(.73;2.24)	
N_ϕ/δ_{RP}	-.06(1.0)(.12)(-.014)	

TABLE I-3

FLIGHT DIRECTOR TRANSFER FUNCTIONS

(a) Hover - H_{BAR}/δ_{ES}

CONTROL CONFIG	FLT. NO./DISPLAY	H_{BAR}/δ_{ES}
AVSAS	F-164/ED2-2 F-165/AV8-6 F-165/AV8-3 F-166/AV8-6	$\frac{-.18(5.26)(.99)(.22)(.061)(.012)}{(0)(.20)(.15)(-.035)(.040)(3.76)}$
AVSAS	F-178/ED2-2 F-179/AV8-6 F-181/ED2-2	$\frac{-.35(1.71)(1.61)(.22)(.061)(.012)}{(0)(.20)(.15)(-.035)(.040)(3.76)}$
RCAH 2	F-169/AV8-3	$\frac{-.27[.91;1.92](.22)(.061)(.012)}{(0)(.20)(.15)(-.036)(.041)(3.55)}$
ACAH 1	F-164/AV8-6 F-165/ED2-2 F-166/AV8-6	$\frac{-.55(4.22)[.93;.29](.065)(.012)}{(0)(.20)(1.53)(.66)(.14)(.0062)}$
ACAH 1	F-180/ED2-2	$\frac{-1.12(1.86)[.93;.31](.065)(.012)}{(0)(.20)(1.53)(.66)(.14)(.0062)}$
ACAH 1.5	F-179/AV8-3	$\frac{-.69(2.11)(.54)(.26)(.063)(.012)}{(0)(.20)[.98;1.44](.14)(.0090)}$

TABLE I-3 (Cont.)

FLIGHT DIRECTOR TRANSFER FUNCTIONS

(b) 65 Knots - H_{BAR}/δ_{ES}

CONTROL CONFIG	FLT. NO./DISPLAY	H_{BAR}/δ_{ES}
AVSAS	F-164/ED2-2 F-165/AV8-6 F-165/AV8-3 F-166/AV8-6	$\frac{-.18(4.42)(2.34)[.94;.22]}{(.20)(-.14)(.17)(.49)(4.11)}$
AVSAS	F-178/ED2-2 F-179/AV8-6 F-181/ED2-2	$\frac{-.36[.80;2.30][.94;.22]}{(.20)(-.14)(.17)(.49)(4.11)}$
RCAH 2	F-169/AV8-3	$\frac{-.27[.74;2.60][.95;.22]}{(.20)(-.15)(.18)(.49)(3.89)}$
ACAH 1	F-164/AV8-6 F-165/ED2-2 F-166/AV8-6	$\frac{-.57(3.94)(1.03)[.84;.20]}{(.20)(1.99)[.96;.53](-.031)}$
ACAH 1	F-180/ED2-2	$\frac{-1.17[.93;1.39][.84;.20]}{(.20)(1.99)[.96;.53](-.031)}$
ACAH 1.5	F-179/AV8-3	$\frac{-.72[.90;1.70][.88;.21]}{(.20)(2.19)(.87)(.58)(.017)}$

TABLE I-3 (Cont.)

FLIGHT DIRECTOR TRANSFER FUNCTIONS

(c) Hover - V_{TAB}/δ_T

CONTROL CONFIG	FLT. NO./DISPLAY	V_{TAB}/δ_T
AVSAS	F-158/AV8-0 F-164/ED2-2 F-165/AV8-6 F-165/AV8-3 F-166/AV8-6 F-167/AV8-0	$\frac{-1.28(3.83)(.20)(.15)(.10)(.0016)}{(0)(.20)(.15)(-.035)(.040)(3.76)}$
AVSAS	F-178/ED2-2 F-178/AV8-0 F-179/AV8-6 F-181/ED2-2	$\frac{-3.39(3.83)(.20)(.15)(.050)(.0016)}{(0)(.20)(.15)(-.035)(.040)(3.76)}$
RCAH 2	F-169/AV8-3	$\frac{-3.39(3.61)(.20)(.15)(.050)(.0017)}{(0)(.20)(.15)(-.036)(.040)(3.55)}$
ACAH 1	F-164/AV8-6 F-165/ED2-2 F-166/AV8-6	$\frac{-1.28(1.55)(.67)(.20)(.14)(.10)}{(0)(.20)(1.53)(.66)(.14)(.0062)}$
ACAH 1	F-180/ED2-2	$\frac{-3.39(1.55)(.67)(.20)(.14)(.05)}{(0)(.20)(1.53)(.66)(.14)(.0062)}$
ACAH 1.5	F-159/AV8-0 F-160/AV8-0	$\frac{-1.28[.98;1.46](.20)(.14)(.10)}{(0)(.20)[.98;1.44](.14)(.0090)}$
ACAH 1.5	F-179/AV8-0 F-179/AV8-3	$\frac{-3.39[.98;1.46](.20)(.14)(.005)}{(0)(.20)[.98;1.44](.14)(.0090)}$

TABLE I-3 (Cont.)

FLIGHT DIRECTOR TRANSFER FUNCTIONS

(d) 65 Knots - V_{TAB}/δ_T

CONTROL CONFIG	FLT. NO./DISPLAY	V_{TAB}/δ_T
AVSAS	F-158/AV8-0 F-164/ED2-2 F-165/AV8-6 F-165/AV8-3 F-166/AV8-6 F-167/AV8-0	$\dfrac{-1.13(4.34)(-.14)(.20)(.17)(.10)}{(0)(.20)(-.14)(.17)(.49)(4.11)}$
AVSAS	F-178/ED2-2 F-178/AV8-0 F-179/AV8-6 F-181/ED2-2	$\dfrac{-3.02(4.34)(-.14)(.20)(.17)(.050)}{(0)(.20)(-.14)(.17)(.49)(4.11)}$
RCAH 2	F-169/AV8-3	$\dfrac{-3.02(4.12)(-.15)(.20)(.17)(.050)}{(0)(.20)(-.15)(.18)(.49)(3.89)}$
ACAH 1	F-164/AV8-6 F-165/ED2-2 F-166/AV8-6	$\dfrac{-1.13(2.38)[.63;.24](.20)(.10)}{(0)(.20)(2.0)[.96;.53](.031)}$
ACAH 1	F-180/ED2-2	$\dfrac{-3.02(2.38)[.63;.24](.20)(.050)}{(0)(.20)(2.0)[.96;.53](.031)}$
ACAH 1.5	F-159/AV8-0 F-160/AV8-0	$\dfrac{-1.13(2.63)[.95;.39](.20)(.10)}{(0)(.20)(2.19)(.87)(.58)(.017)}$
ACAH 1.5	F-179/AV8-0 F-179/AV8-3	$\dfrac{-3.02(2.63)[.95;.39](.20)(.050)}{(0)(.20)(2.19)(.87)(.58)(.017)}$

TABLE I-3 (Cont.)

FLIGHT DIRECTOR TRANSFER FUNCTIONS

(e) Hover - V_{BAR}/δ_{AS} - YRC/HH

CONTROL CONFIG	FLT. NO./DISPLAY	V_{BAR}/δ_{AS}
AVSAS	F-158/AV8-0	$\frac{.30(4.40)[.77;1.07](1.09)(.39)(.011)}{(0)(.30)(3.04)[.33;.18][.77;1.07]}$
AVSAS	F-164/ED2-2	$\frac{7.16(2.40)[.77;1.07][.60;.18](.012)}{(0)(.30)(3.04)[.33;.18][.77;1.07]}$
AVSAS	F-165/AV8-6 F-165/AV8-3	$\frac{2.92(5.58)[.77;1.07][.61;.18](.012)}{(0)(.30)(3.04)[.33;.18][.77;1.07]}$
AVSAS	F-166/AV8-6 F-167/AV8-0 F-178/ED2-2 F-178/AV8-0 F-179/AV8-6 F-181/ED2-2	$\frac{1.95(3.10)[.77;1.07][.67;.30](.011)}{(0)(.30)(3.04)[.33;.18][.77;1.07]}$
RCAH 2	F-169/AV8-3	$\frac{.30[.68;2.36][.77;1.07](.34)(.011)}{(0)(.30)(3.22)[.34;.17][.77;1.07]}$
ACAH 1	F-164/AV8-6	$\frac{.76[.79;1.39][.77;1.07](.39)(.011)}{(0)(.30)[.72;2.24](.14)[.77;1.06]}$
ACAH 1 ACAH 1.5	F-165/ED2-2 F-159/AV8-0 F-160/AV8-0	$\frac{.30(4.40)[.77;1.07](1.09)(.39)(.011)}{(0)(.30)[.72;2.24](.14)[.77;1.06]}$
ACAH 1 ACAH 1.5	F-166/AV8-6 F-180/ED2-2 F-179/AV8-0 F-179/AV8-3	$\frac{.30[.68;2.36][.77;1.07](.34)(.011)}{(0)(.30)[.72;2.24](.14)[.77;1.06]}$

TABLE I-3 (Cont.)

FLIGHT DIRECTOR TRANSFER FUNCTIONS

(f) Hover - V_{BAR}/δ_{AS} - ATC

CONTROL CONFIG	FLT. NO./DISPLAY	V_{BAR}/δ_{AS}
AVSAS	F-158/AV8-0	$\frac{.30(3.73)(1.85)(.73)(.019)(.010)}{(0)(3.07)[.32;.16](.74)(.022)}$
AVSAS	F-164/ED2-2	$\frac{7.16(2.06)(.73)(.25)(.019)(.0057)}{(0)(3.07)[.32;.16](.74)(.022)}$
AVSAS	F-165/AV8-6 F-165/AV8-3	$\frac{2.92(5.26)(.73)(.24)(.019)(.0057)}{(0)(3.07)[.32;.16](.74)(.022)}$
AVSAS	F-166/AV8-6 F-167/AV8-0 F-178/ED2-2 F-178/AV8-6 F-179/AV8-0 F-181/ED2-2	$\frac{1.95(2.72)(.73)(.49)(.019)(.0083)}{(0)(3.07)(.053)[.32;.16](.74)(.022)}$
RCAH 2	F-169/AV8-3	$\frac{.30[.63;2.58](1.95)(.011)(.0069)}{(0)(3.20)[.34;.17](1.98)(.0059)}$
ACAH 1	F-164/AV8-6	$\frac{.76(1.95)[.69;1.65](.010)(.0069)}{(0)(1.92)[.72;2.24](.15)(.0068)}$
ACAH 1	F-165/ED2-2 F-159/AV8-0 F-160/AV8-0	$\frac{.30(3.73)(1.95)(1.85)(.010)(.0069)}{(0)(1.92)[.72;2.24](.15)(.0068)}$
ACAH 1 ACAH 1.5	F-166/AV8-6 F-180/ED2-2 F-179/AV8-0 F-179/AV8-3	$\frac{.30[.63;2.58](1.95)(.010)(.0069)}{(0)(1.92)[.72;2.24](.15)(.0068)}$

TABLE I-3 (Cont.)

FLIGHT DIRECTOR TRANSFER FUNCTIONS

(g) 65 Knots - V_{BAR}/δ_{AS} - ATC

CONTROL CONFIG	FLT. NO./DISPLAY	V_{BAR}/δ_{AS}
AVSAS	F-158/AV8-0	$\frac{.29(3.38)(1.36)(1.02)[.84;.56](.011)}{(0)(0)(3.77)[.40;.76](.49)(.021)}$
AVSAS	F-164/ED2-2	$\frac{6.87(2.07)[.53;.93](.28)(.11)(.013)}{(0)(0)(3.77)[.40;.76](.49)(.021)}$
AVSAS	F-165/AV8-6 F-165/AV8-3	$\frac{2.80(5.25)[.54;.92](.28)(.11)(.013)}{(0)(0)(3.77)[.40;.76](.49)(.021)}$
AVSAS	F-166/AV8-6 F-167/AV8-0 F-178/ED2-2 F-178/AV8-0 F-179/AV8-6 F-181/ED2-2	$\frac{1.87(2.70)[.57;.99][.88;.29](.012)}{(0)(0)(3.77)[.40;.76](.49)(.021)}$
RCAH	F-169/AV8-3	$\frac{.30[.64;2.86][.76;.92](.61)(.011)}{(0)(0)(3.92)[.69;1.41](.53)(-.0045)}$
ACAH 1	F-164/AV8-6	$\frac{.76[.68;2.05][.78;.70](.81)(.011)}{(0)(0)[.67;1.75][.93;2.02](.28)}$
ACAH 1 ACAH 1.5	F-165/ED2-2 F-159/AV8-0 F-160/AV8-0	$\frac{.30(2.99)(2.49)(1.47)[.84;.62](.011)}{(0)(0)[.67;1.75][.93;2.02](.28)}$
ACAH 1 ACAH 1.5	F-166/AV8-6 F-180/ED2-2 F-179/AV8-0 F-179/AV8-3	$\frac{.30[.64;2.86][.76;.92](.61)(.011)}{(0)(0)[.67;1.75][.93;2.02](.28)}$

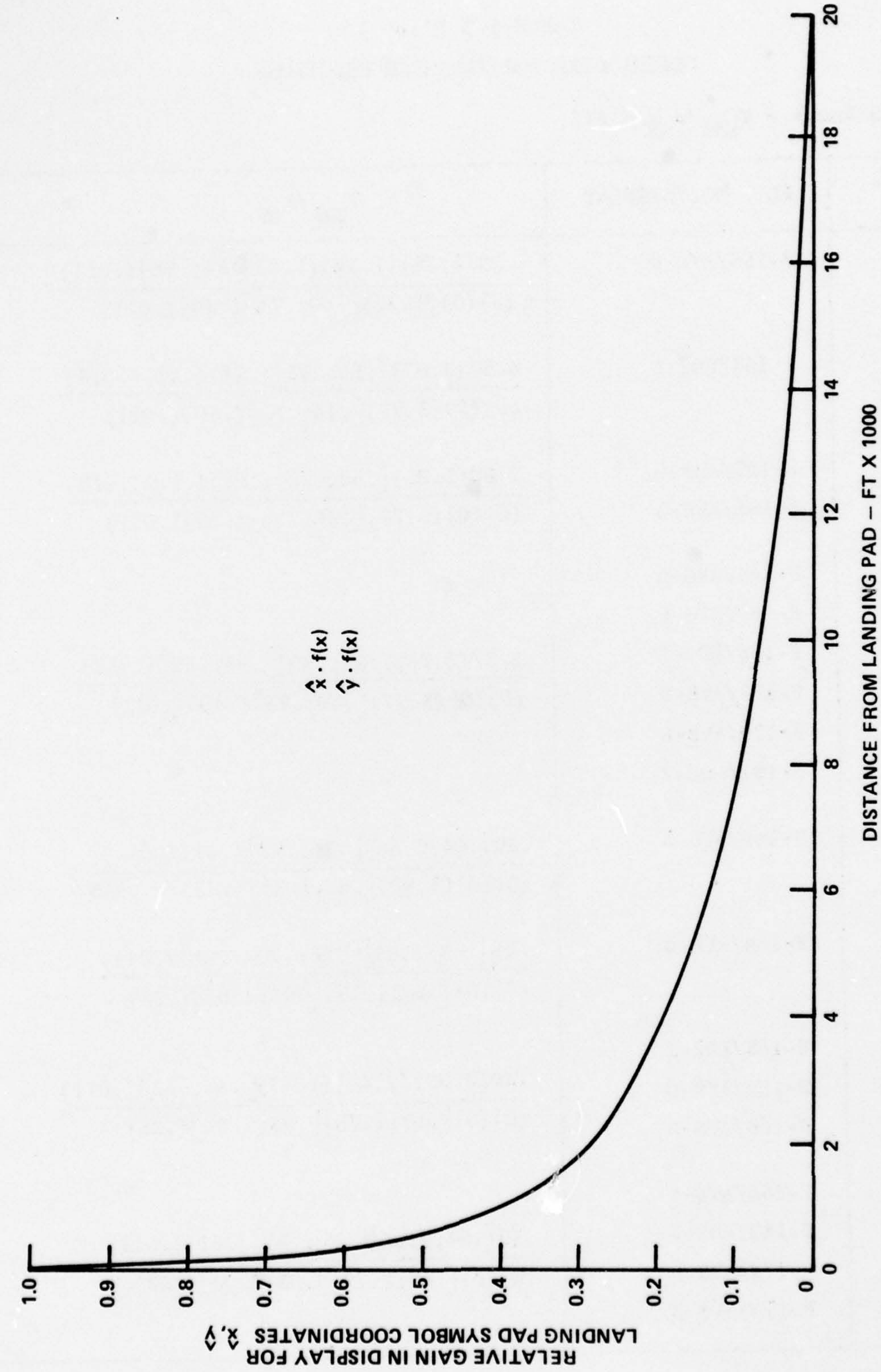

RELATIVE GAIN IN DISPLAY FOR
LANDING PAD SYMBOL COORDINATES $\hat{x}, \hat{y}$
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
$\hat{x} \cdot f(x)$
$\hat{y} \cdot f(x)$
0
2
4
6
8
10
12
14
16
18
20
DISTANCE FROM LANDING PAD – FT X 1000

Figure I-1

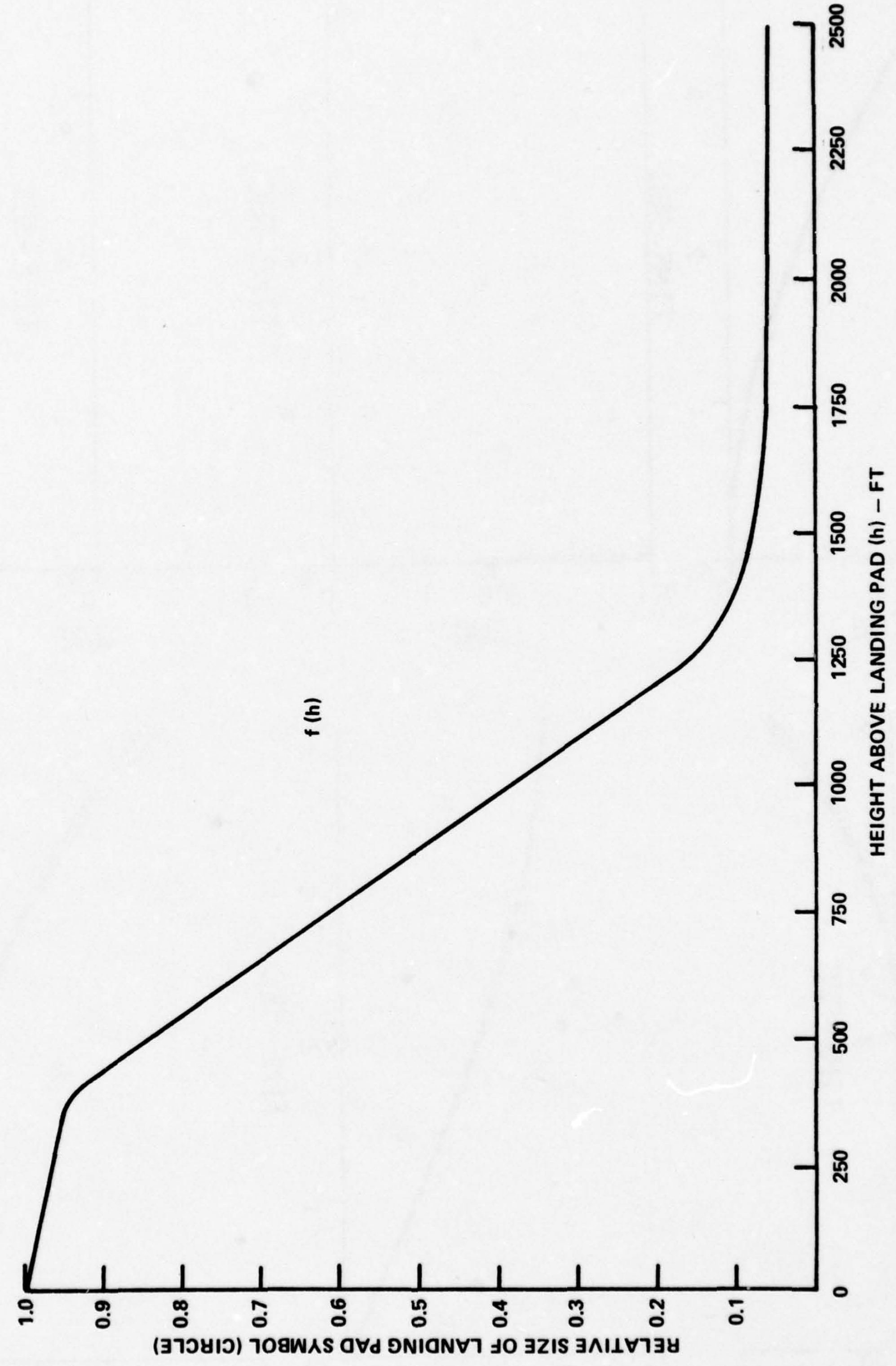


Figure I-2 HEIGHT ABOVE LANDING PAD (h) – FT

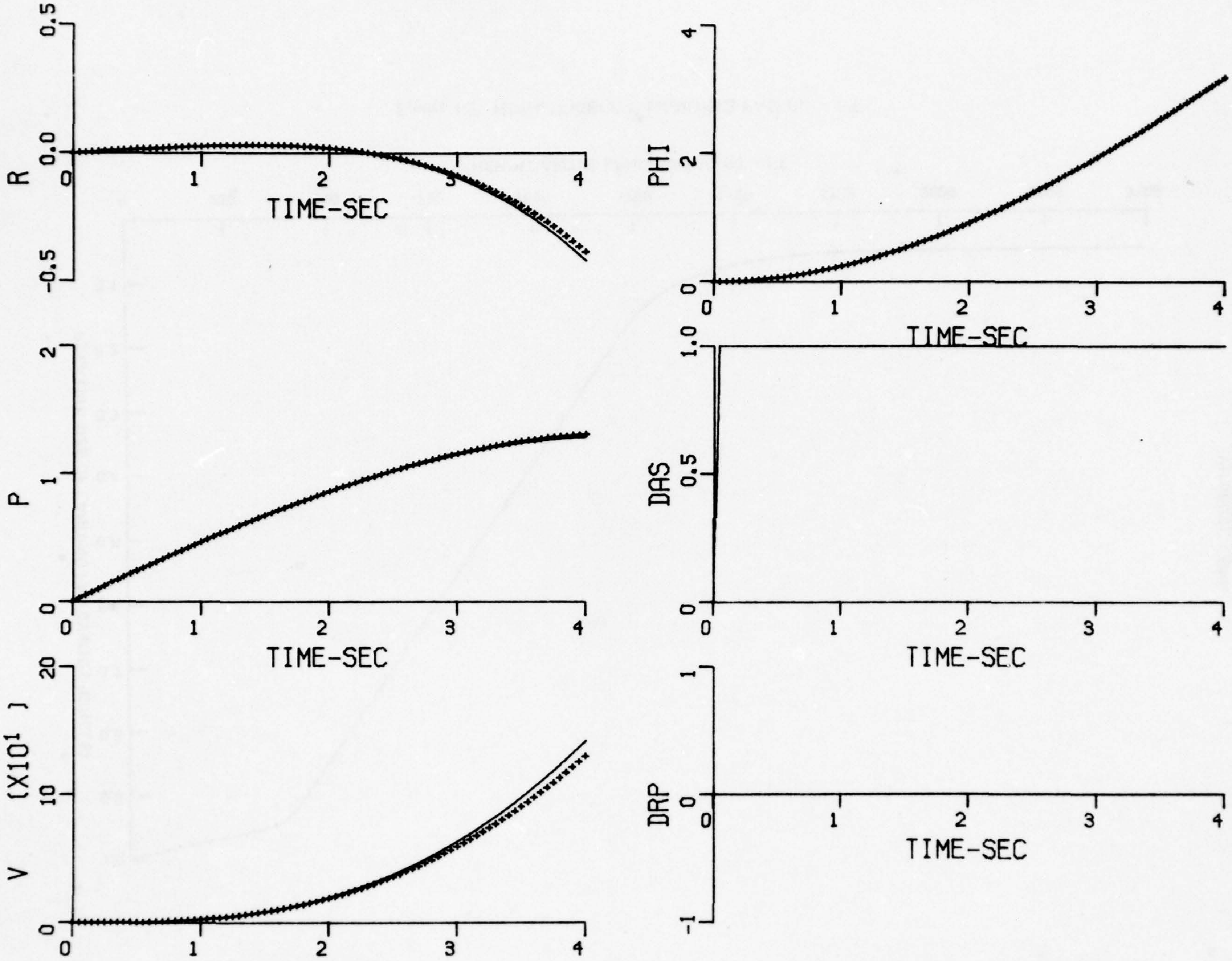


Figure I-3 LATERAL-DIRECTIONAL TIME HISTORIES OF SIMULATION (V = 0 Kt, θ_j = 81 deg, 1 inch δ_{AS} STEP)

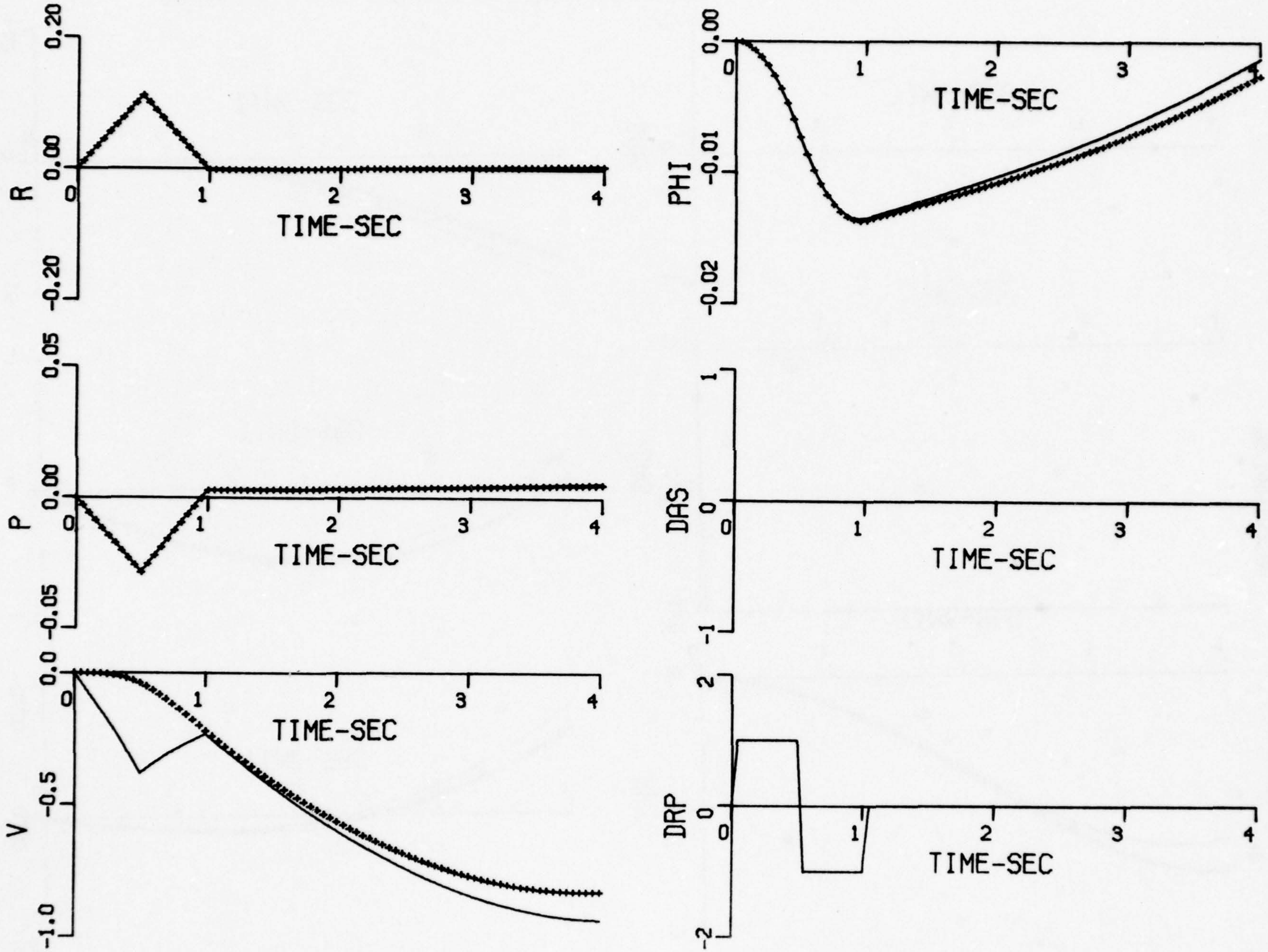


Figure I-3 (Cont) LATERAL-DIRECTIONAL TIME HISTORIES OF SIMULATION (V = 0 Kt, Θ_j = 81 deg, 1 inch δ_{RP} DOUBLET)

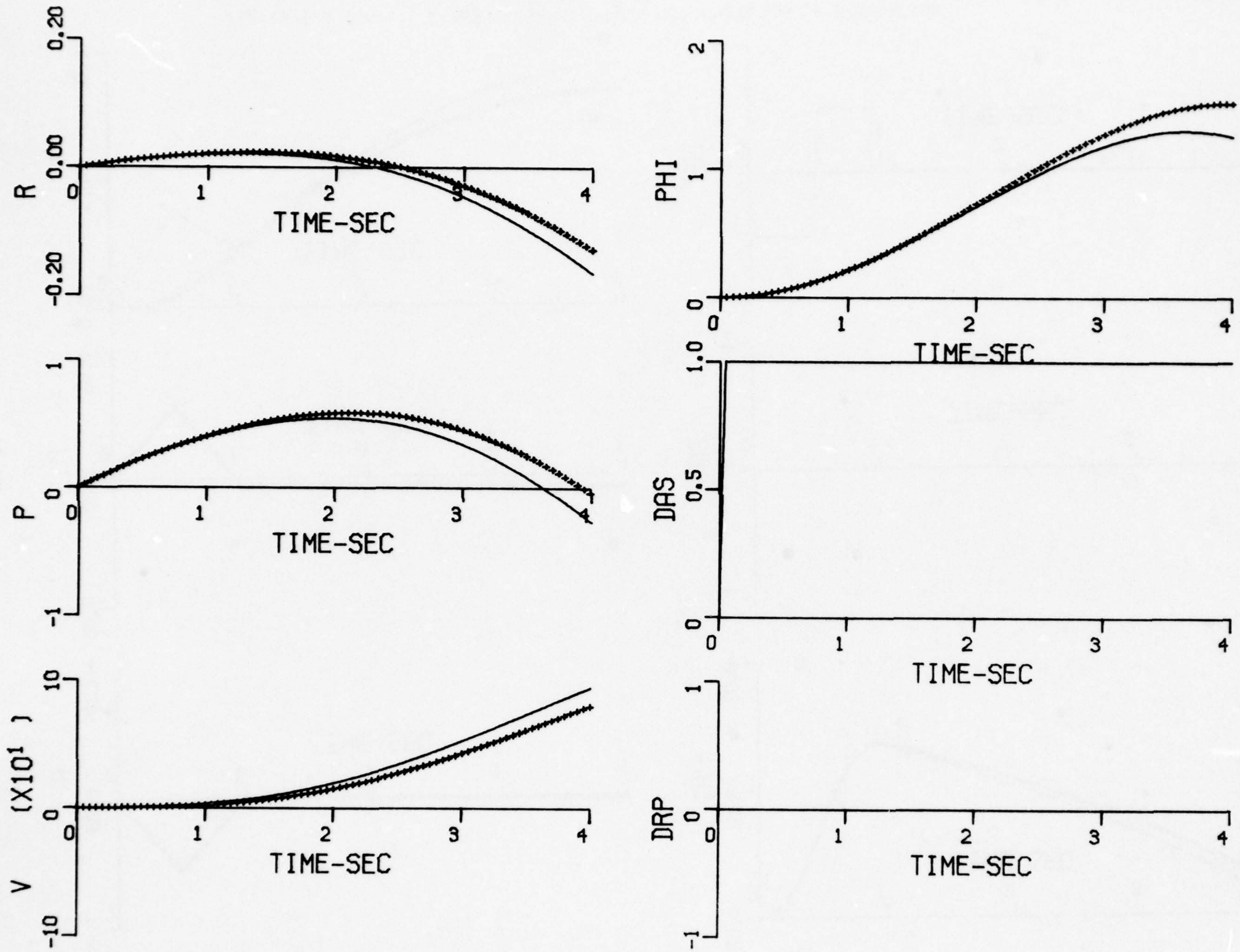


Figure I-3 (Cont) LATERAL-DIRECTIONAL TIME HISTORIES OF SIMULATION (V = 30 Kt, Θ_j = 81 deg, 1 inch δ_{AS} STEP)

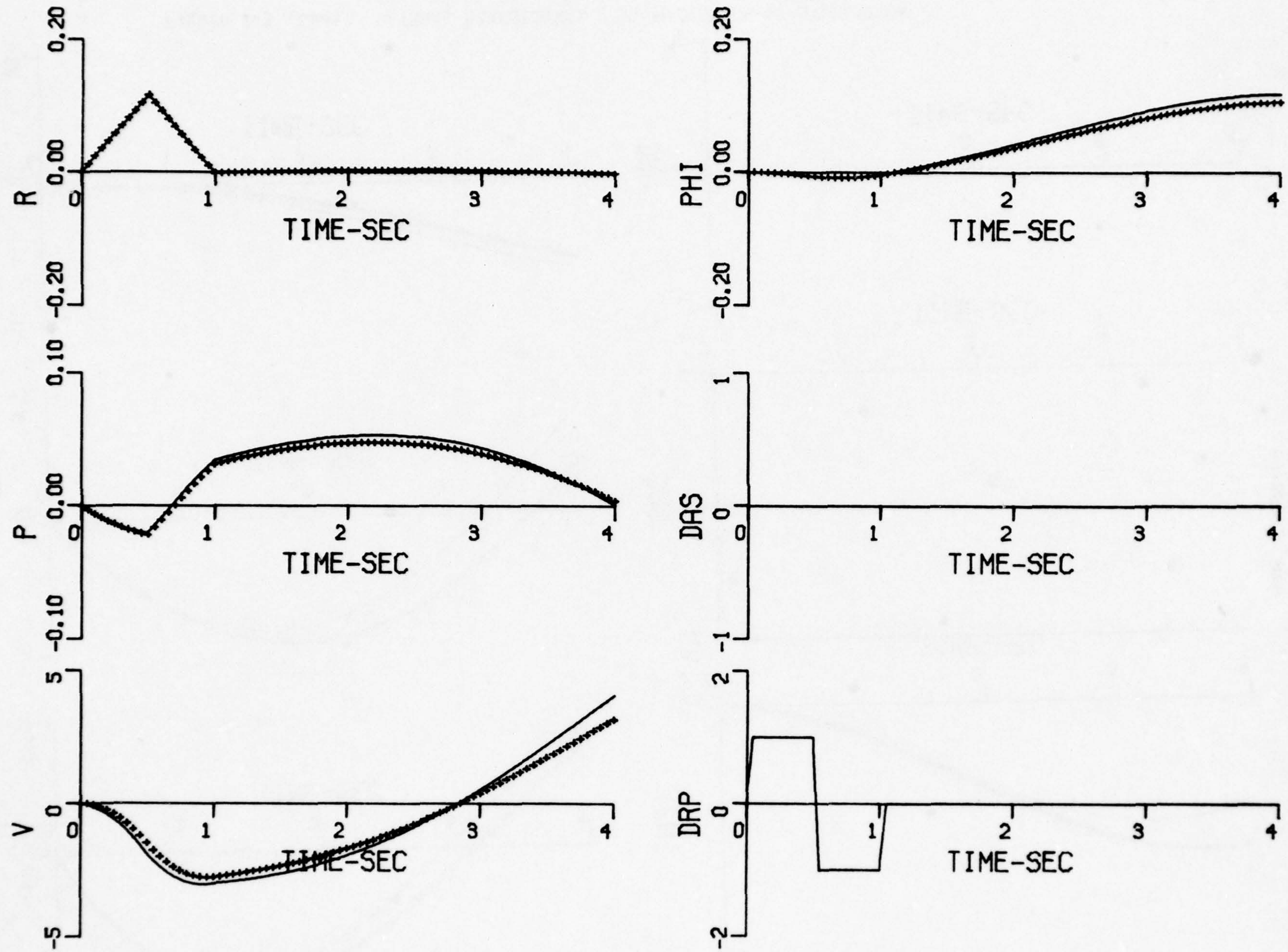


Figure I-3 (Cont) LATERAL-DIRECTIONAL TIME HISTORIES OF SIMULATION
(V = 30 Kt, θ_j = 81 deg, 1 inch δ_{RP} DOUBLET)

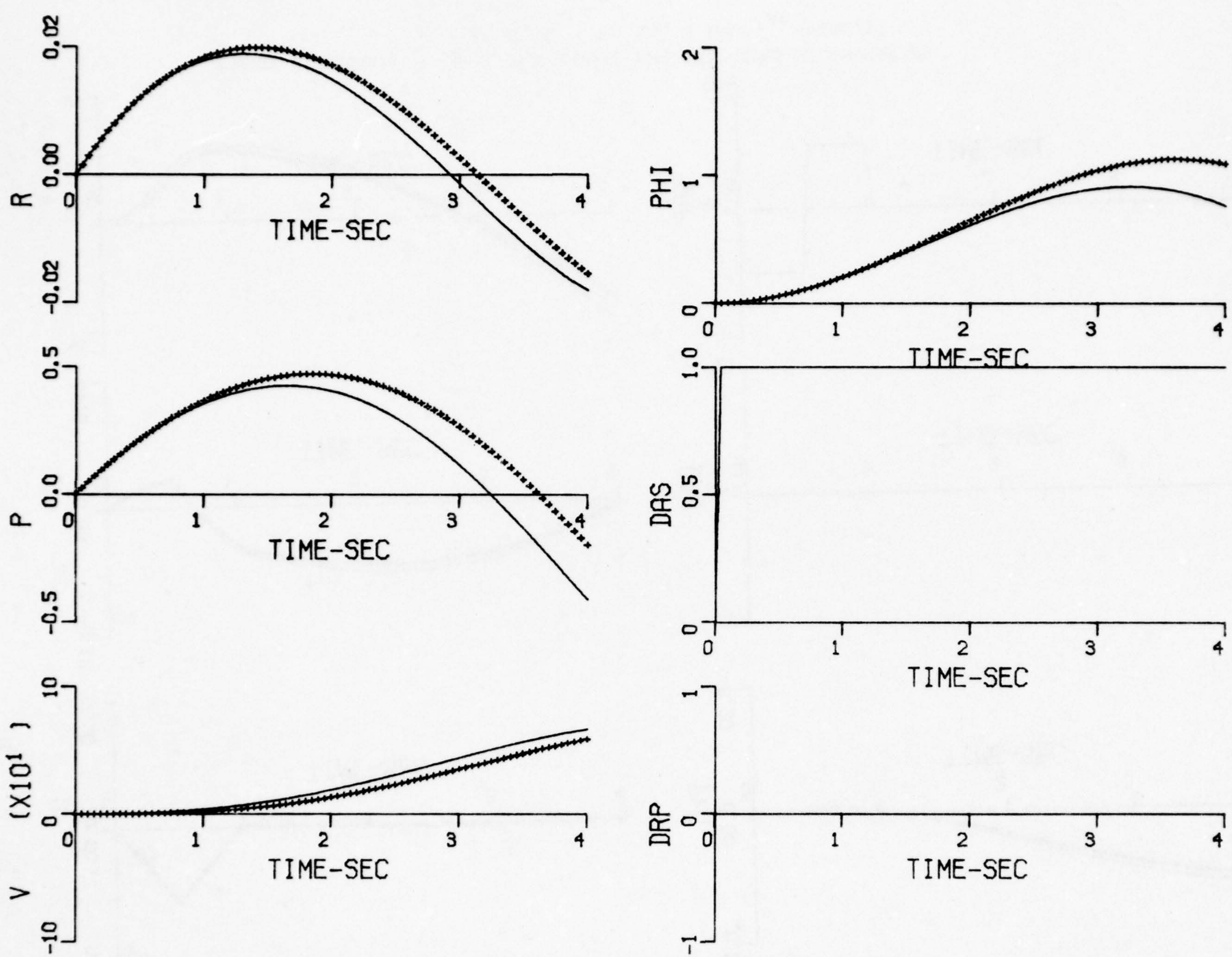


Figure I-3 (Cont) LATERAL-DIRECTIONAL TIME HISTORIES OF SIMULATION (V = 50 Kt, θ_j = 81 deg, 1 inch δ_{AS} STEP)

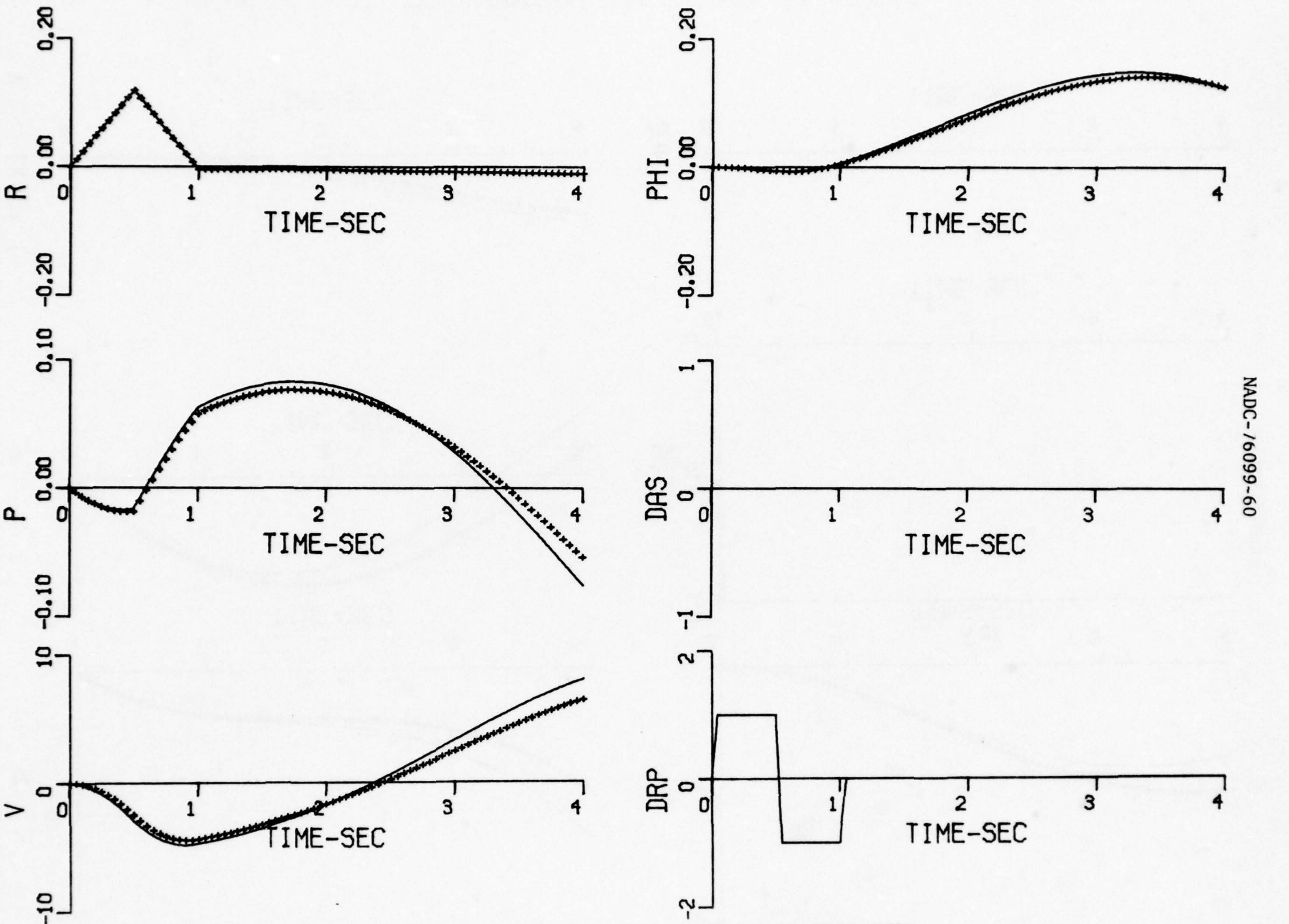


Figure I-3 (Cont) LATERAL-DIRECTIONAL TIME HISTORIES OF SIMULATION
(V = 50 Kt, θ_j = 81 deg, 1 inch δ_{RP} DOUBLET)

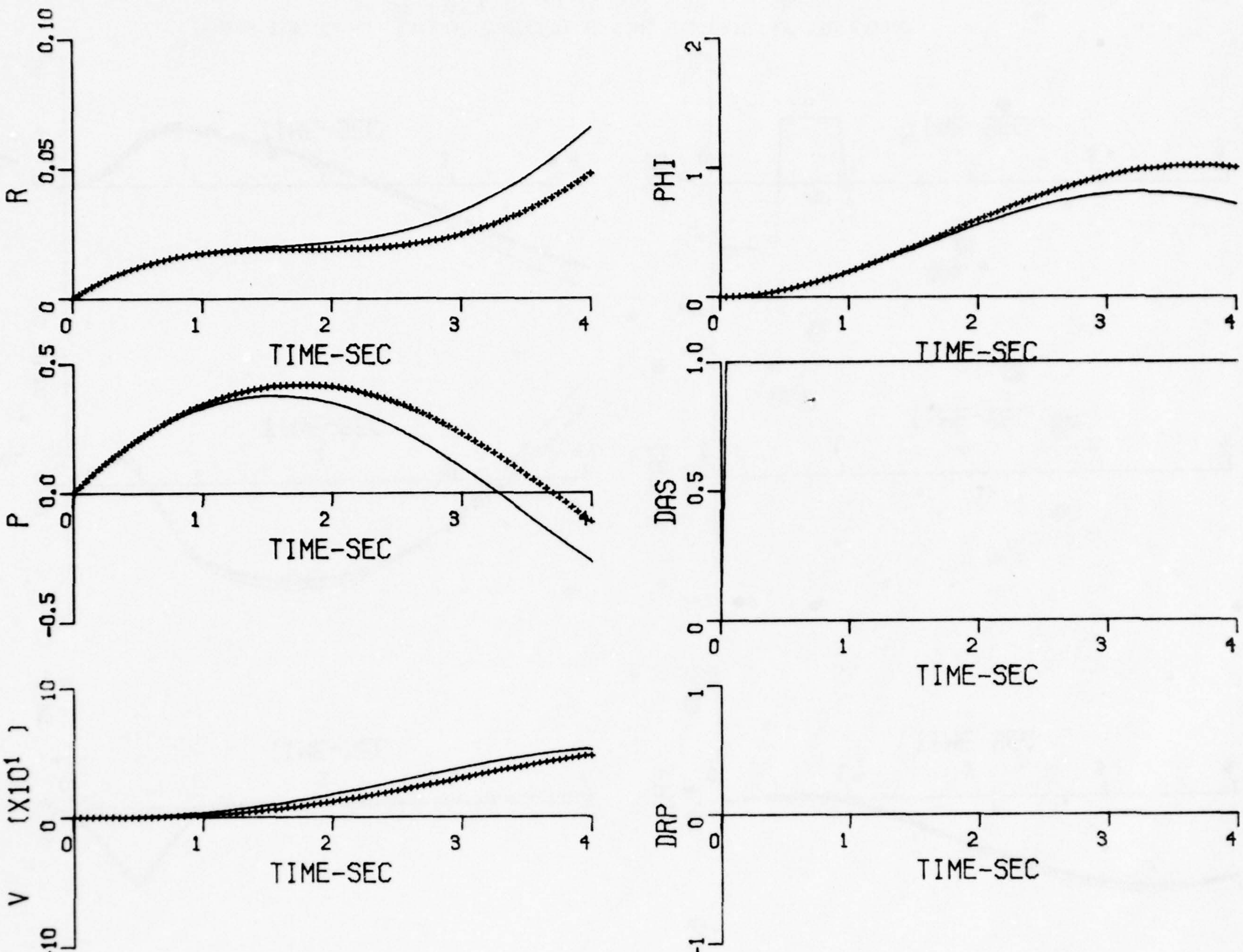


Figure I-3 (Cont) LATERAL-DIRECTIONAL TIME HISTORIES OF SIMULATION
(V = 65 Kt, θ_j = 81 deg, 1 inch δ_{AS} STEP)

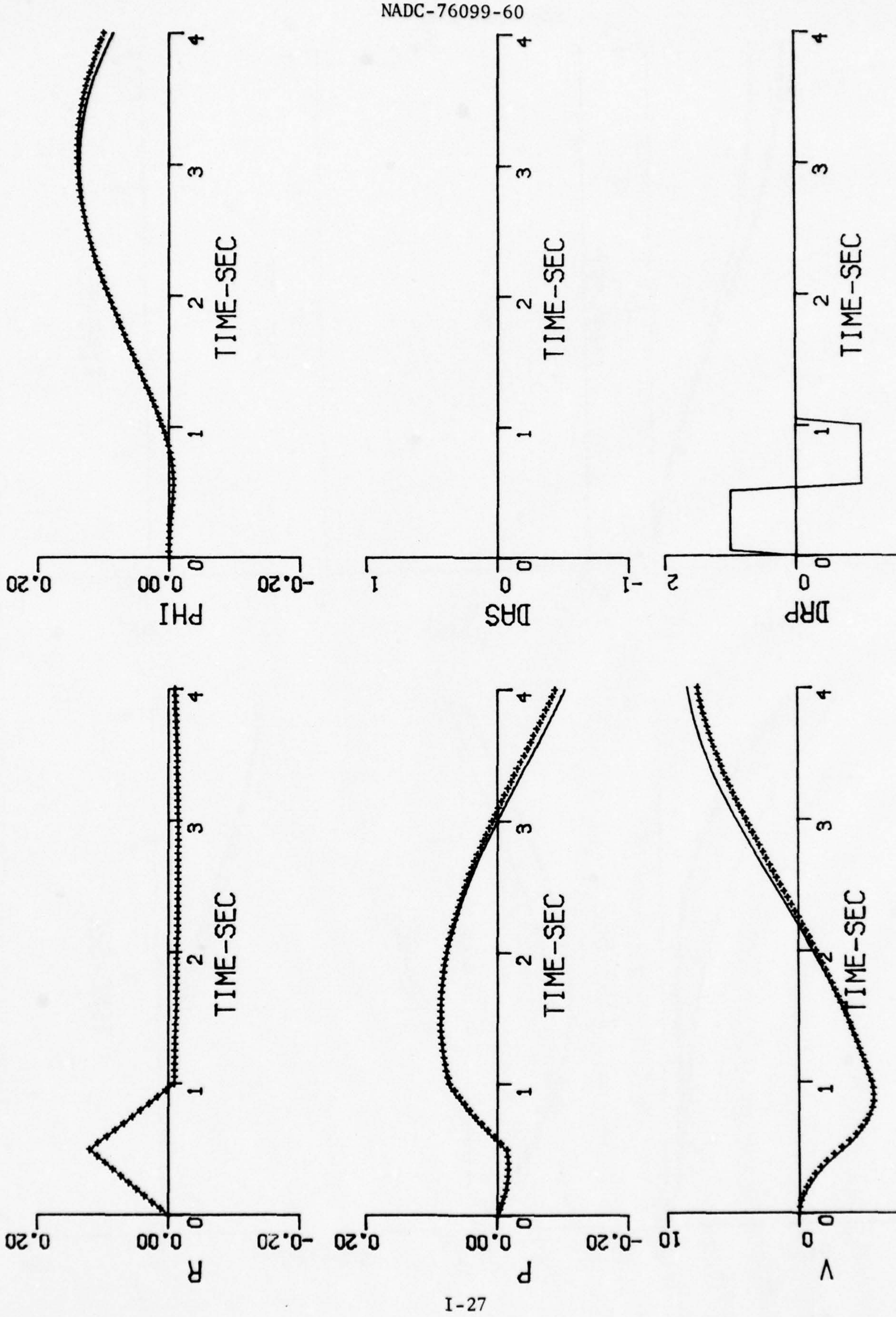


Figure I-3 (Cont) LATERAL-DIRECTIONAL TIME HISTORIES OF SIMULATION
(V = 65 Kt, θ_j = 81 deg, 1 inch δ_{RP} DOUBLET)

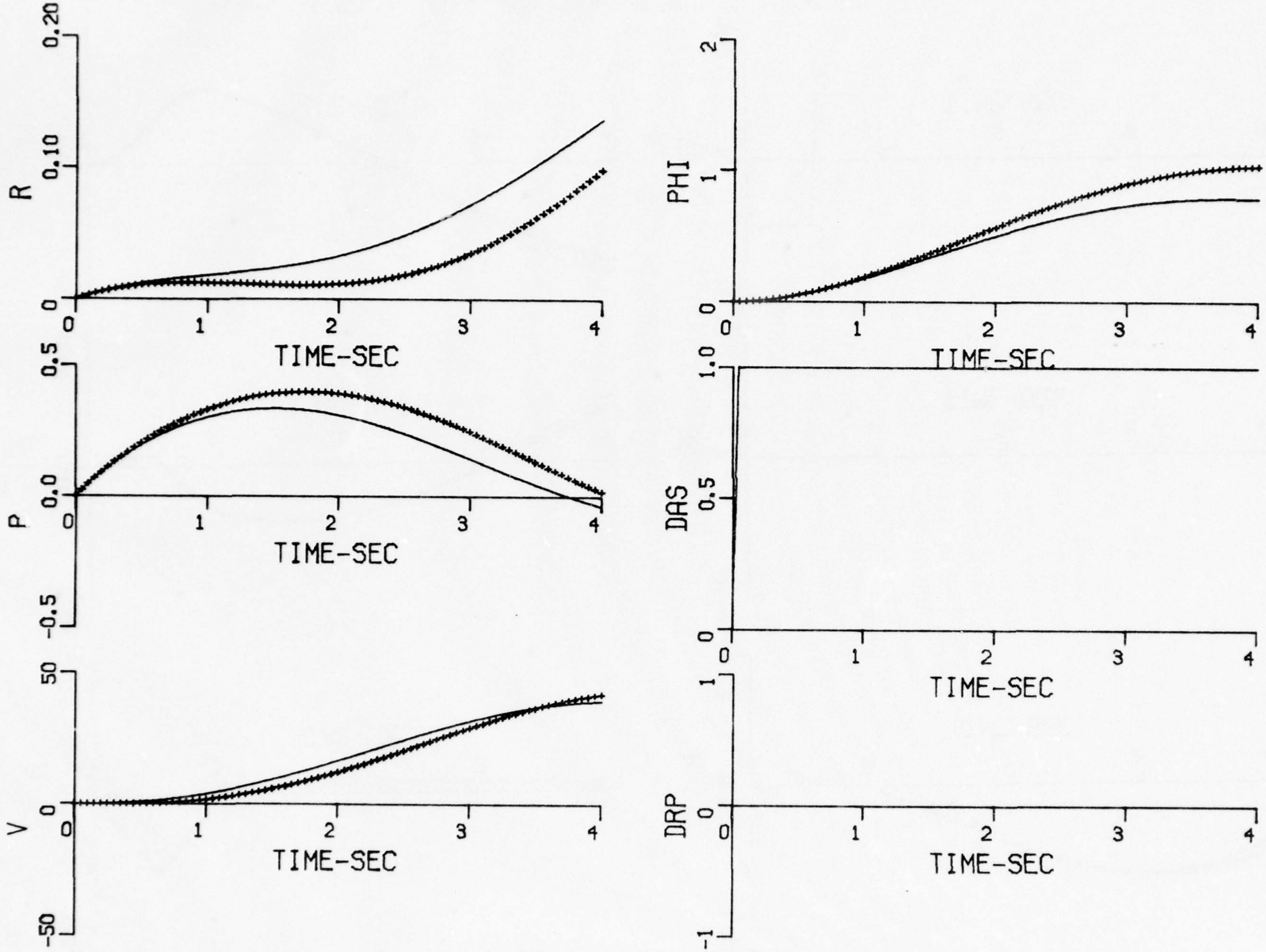


Figure I-3 (Cont) LATERAL-DIRECTIONAL TIME HISTORIES OF SIMULATION (V = 80 Kt, θ_j = 81 deg, 1 inch δ_{AS} STEP)

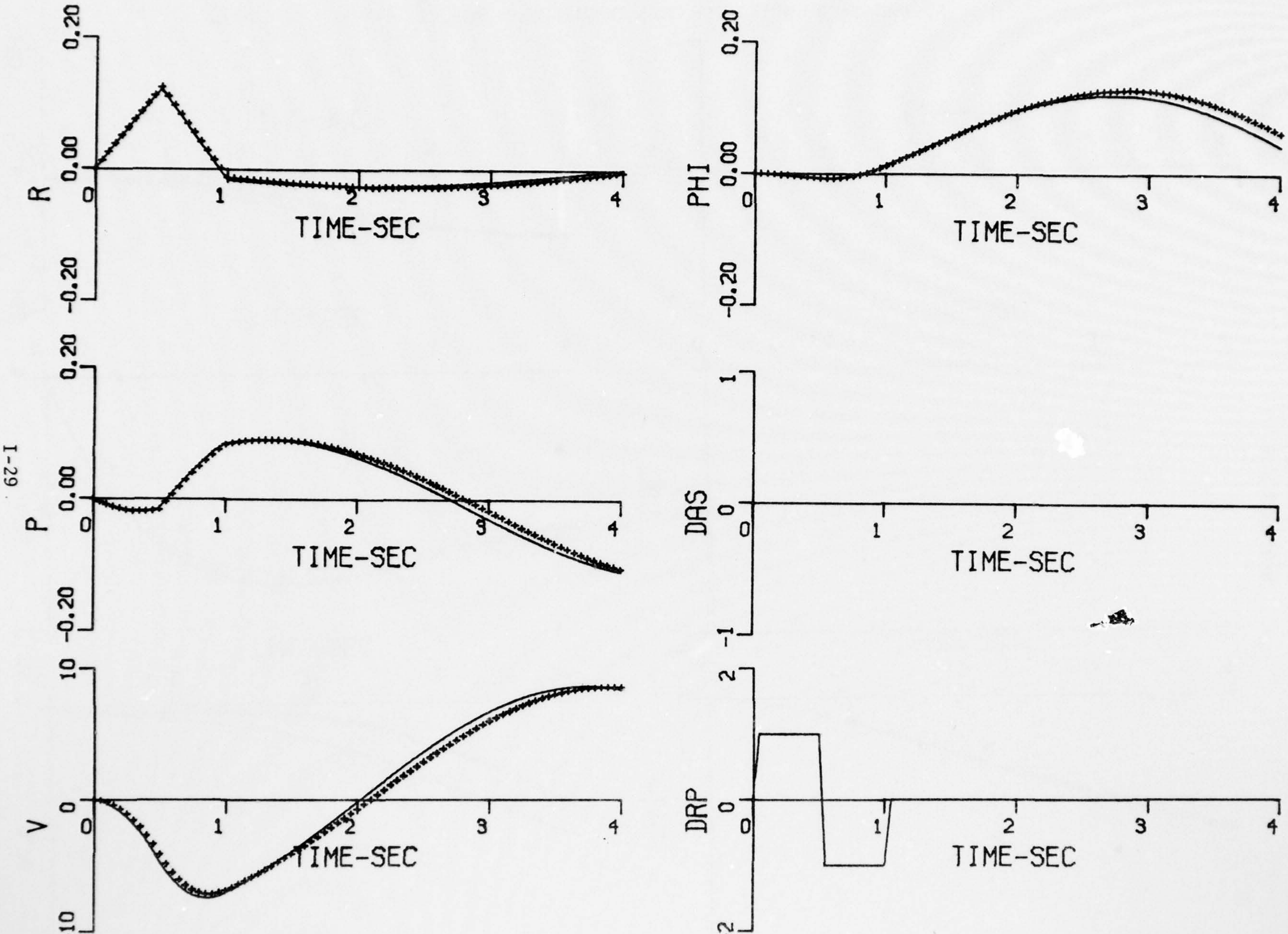


Figure I-3 (Cont) LATERAL-DIRECTIONAL TIME HISTORIES OF SIMULATION
(V = 80 Kt, θ_j = 81 deg, 1 inch δ_{RP} DOUBLET)

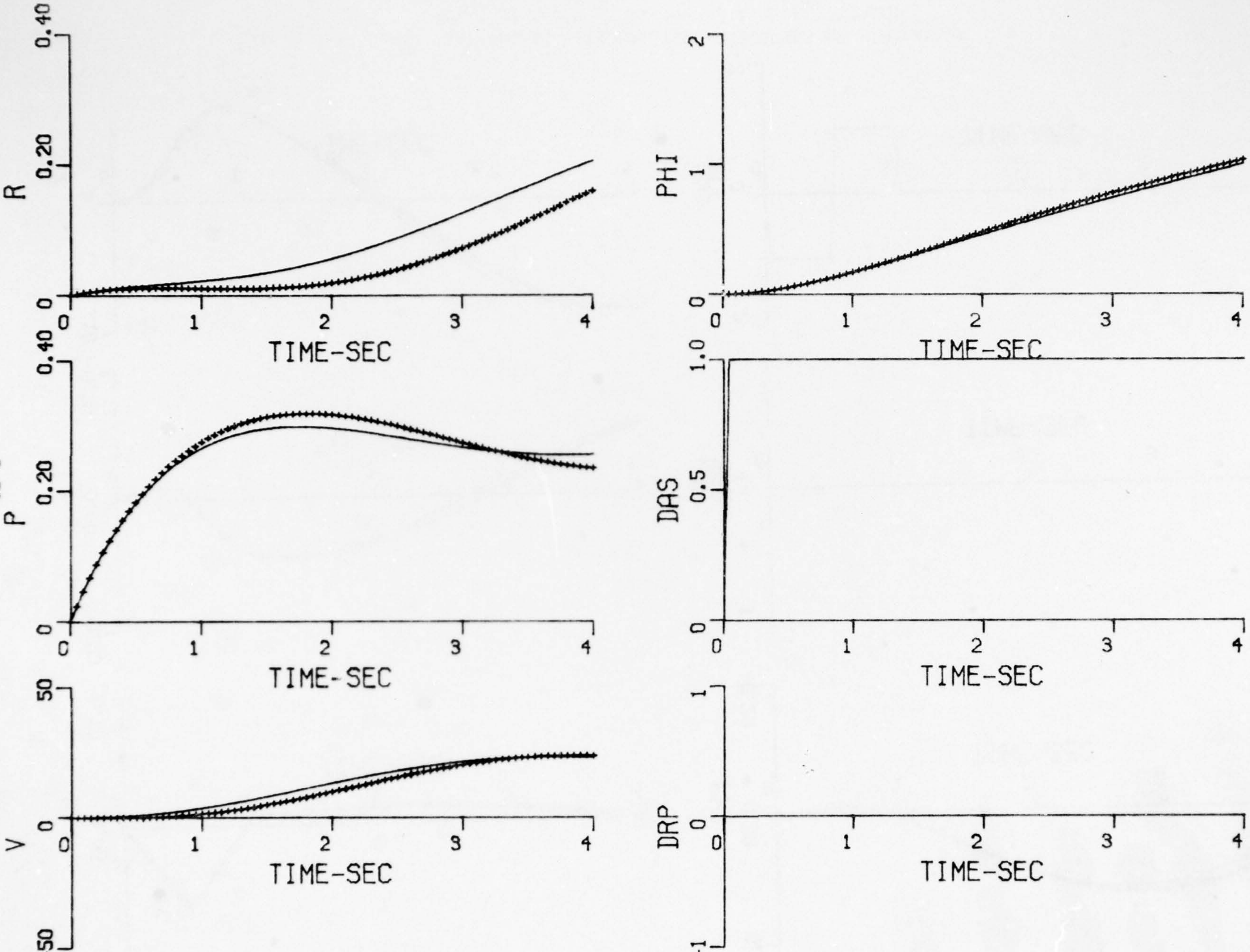


Figure (Cont) LATERAL-DIRECTIONAL TIME HISTORIES OF SIMULATION
(V = 105 Kt, Θ_j = 81 deg, 1 inch δ_{AS} STEP)

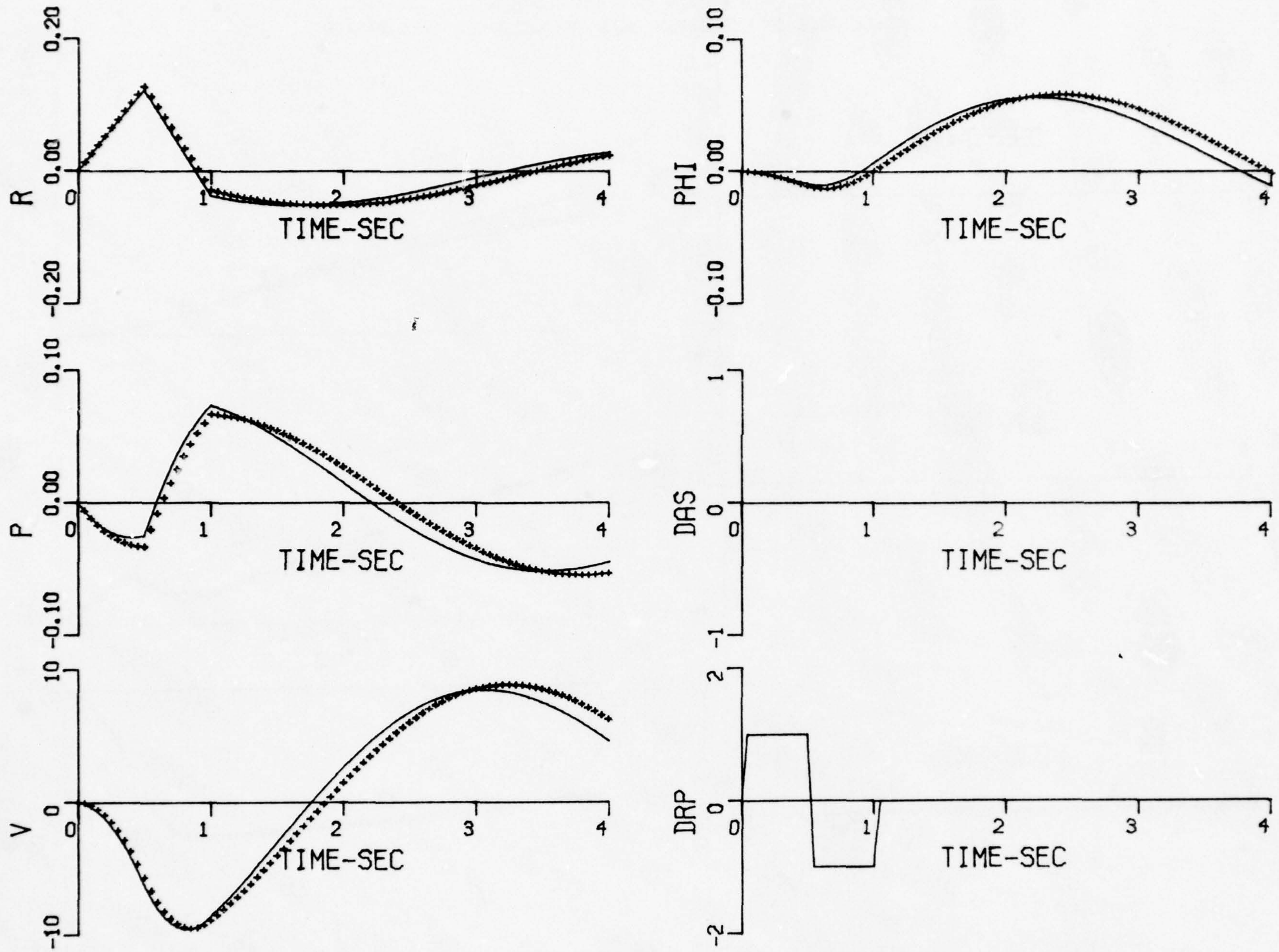


Figure I-3 (Cont) LATERAL-DIRECTIONAL TIME HISTORIES OF SIMULATION (V = 105 Kt, θ_j = 81 deg, 1 inch δ_{RP} DOUBLET)

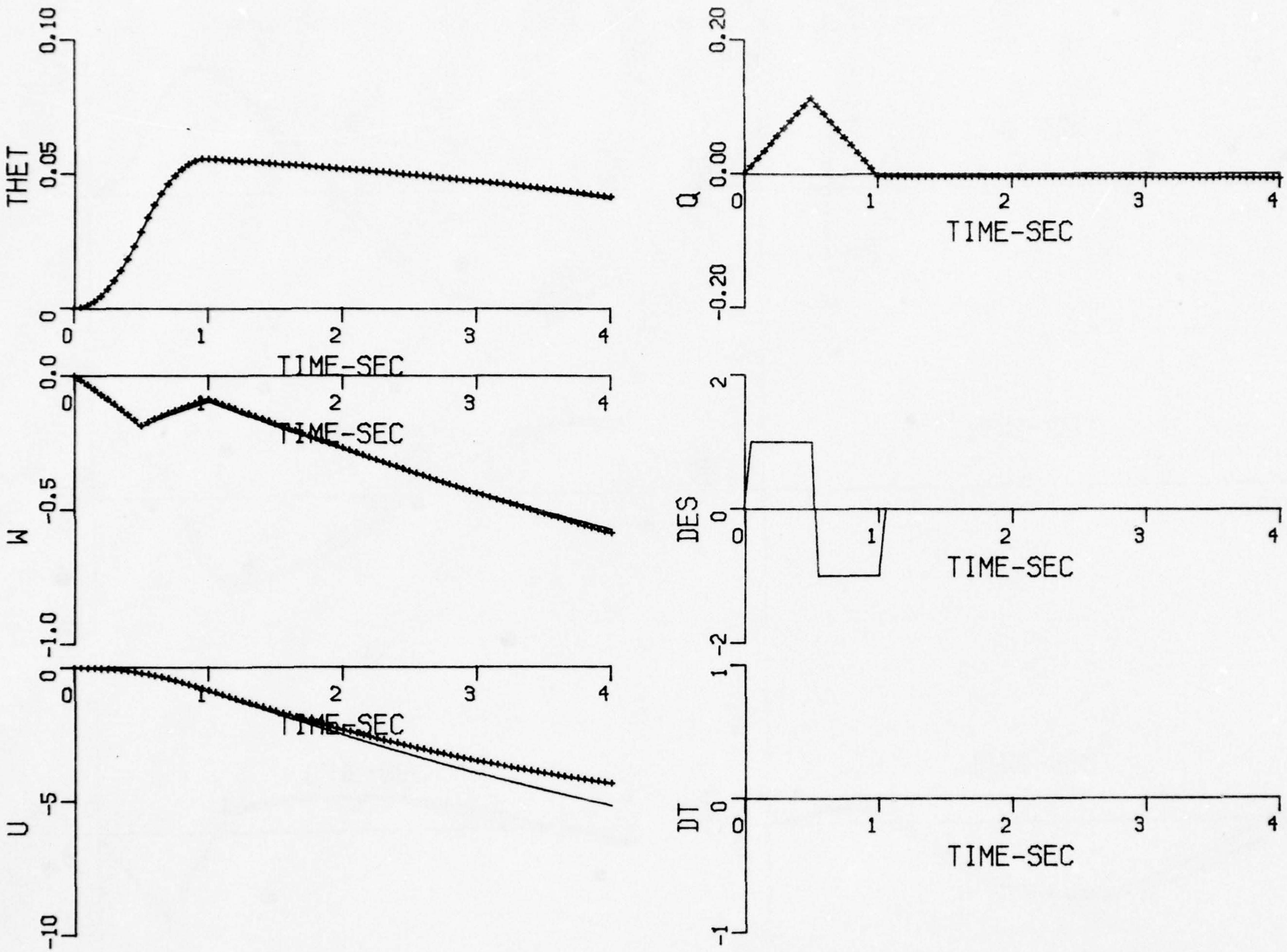


Figure I-4 LONGITUDINAL TIME HISTORIES OF SIMULATION
(V = 0 Kt, Θ_j = 81 deg, 1 inch δ_{ES} DOUBLET)

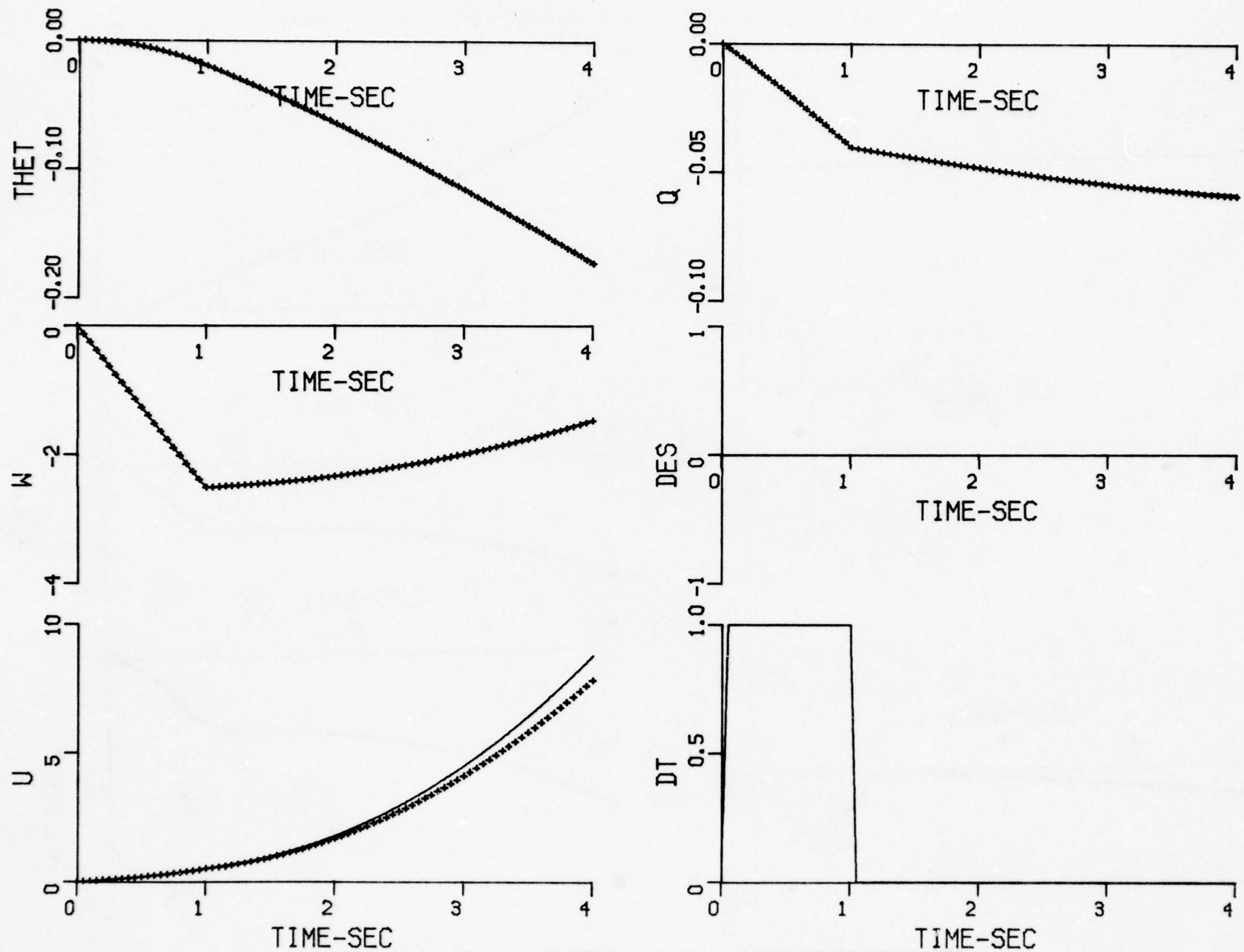


Figure I-4 (Cont) LONGITUDINAL TIME HISTORIES OF SIMULATION
(V = 0 Kt, Θ_j = 81 deg, 1 inch δ_T PULSE)

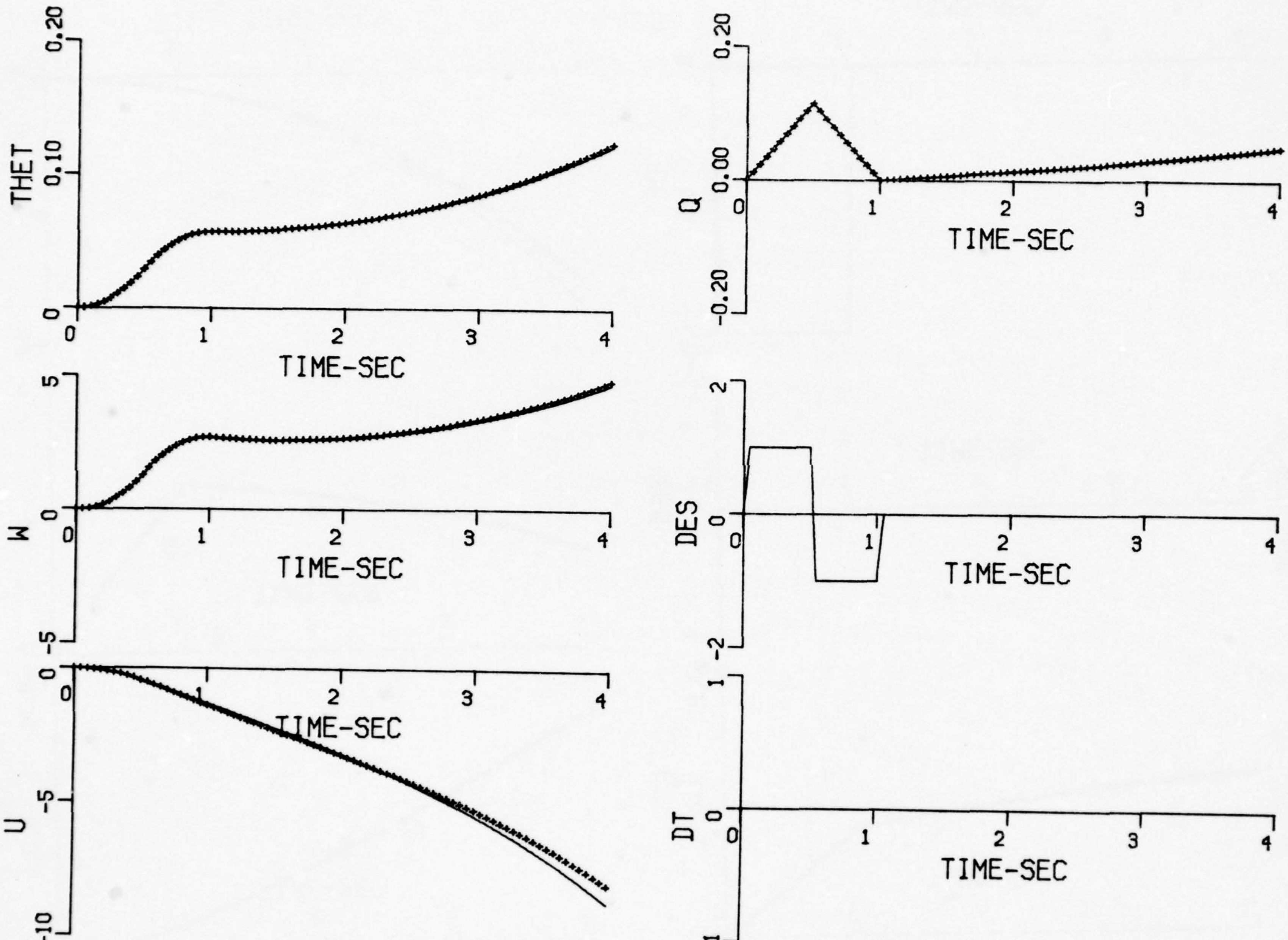


Figure I-4(Cont) LONGITUDINAL TIME HISTORIES OF SIMULATION
(V = 30 Kt, θ_j = 81 deg, 1 inch δ_{ES} DOUBLET)

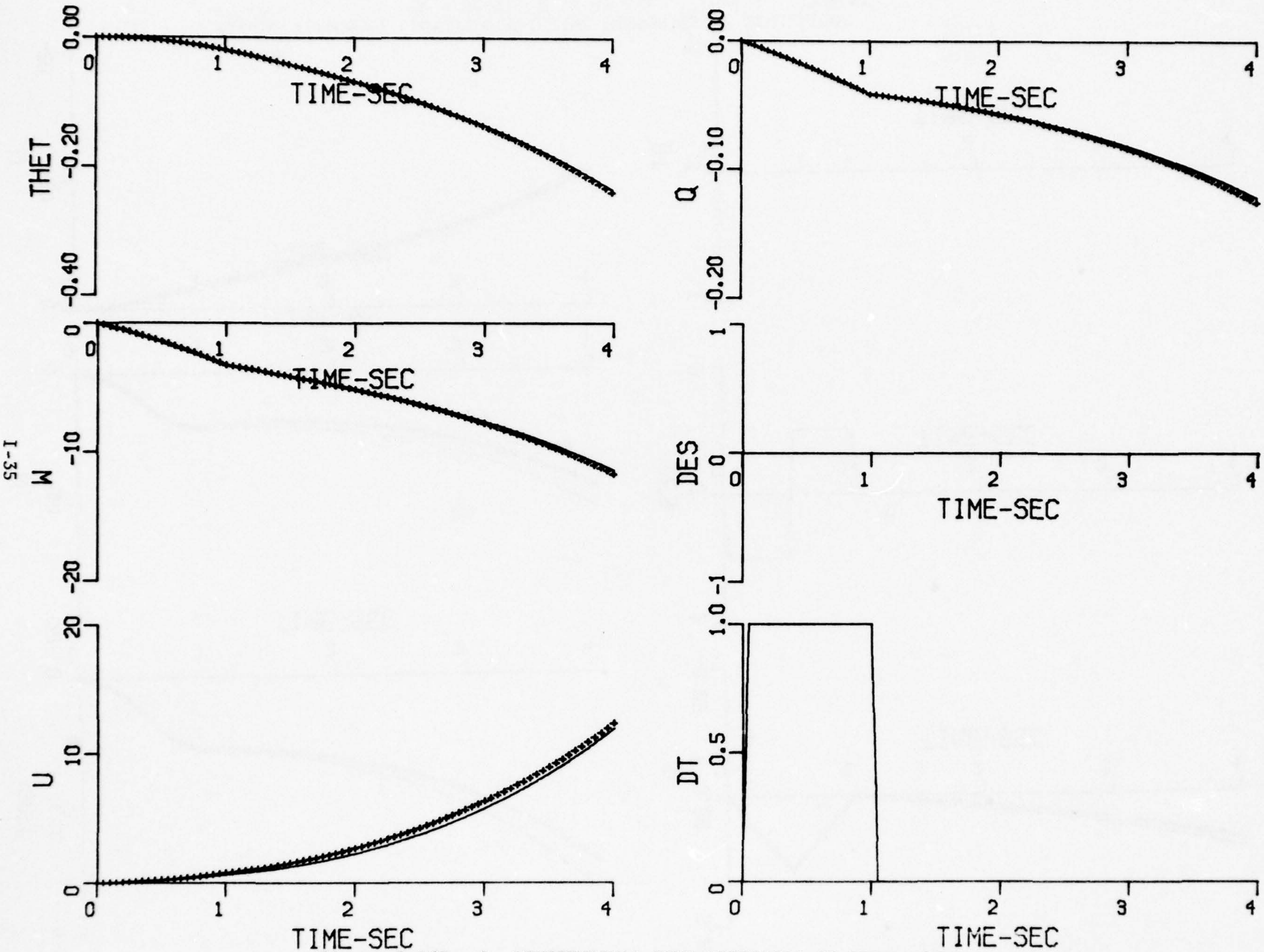


Figure I-4(Cont) LONGITUDINAL TIME HISTORIES OF SIMULATION
(V = 30 Kt, Θ_j = 81 deg, 1 inch δ_T PULSE)

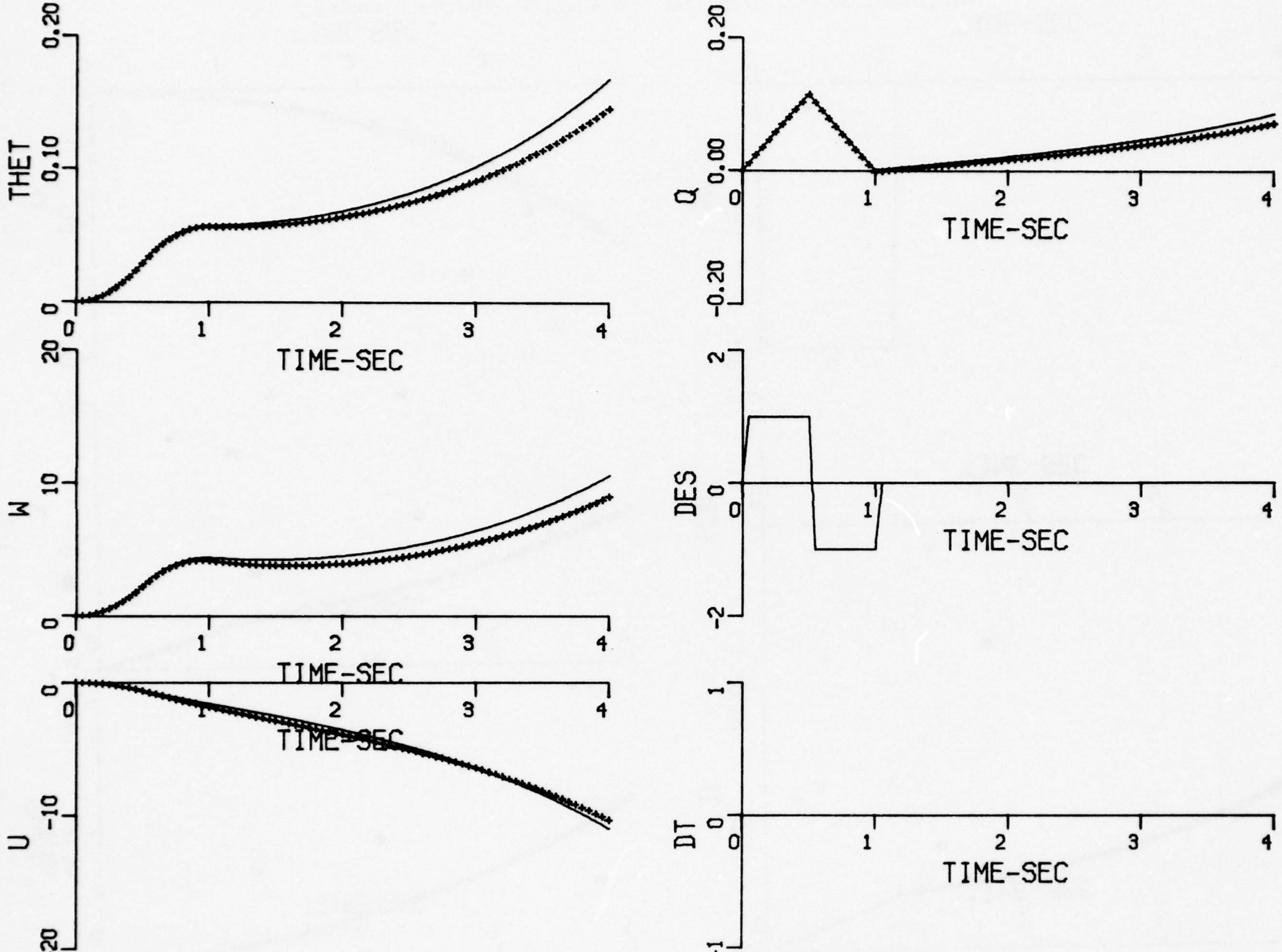


Figure I-4 (Cont) LONGITUDINAL TIME HISTORIES OF SIMULATION
(V = 50 Kt, Θ_j = 81 deg, 1 inch δ_{ES} DOUBLET)

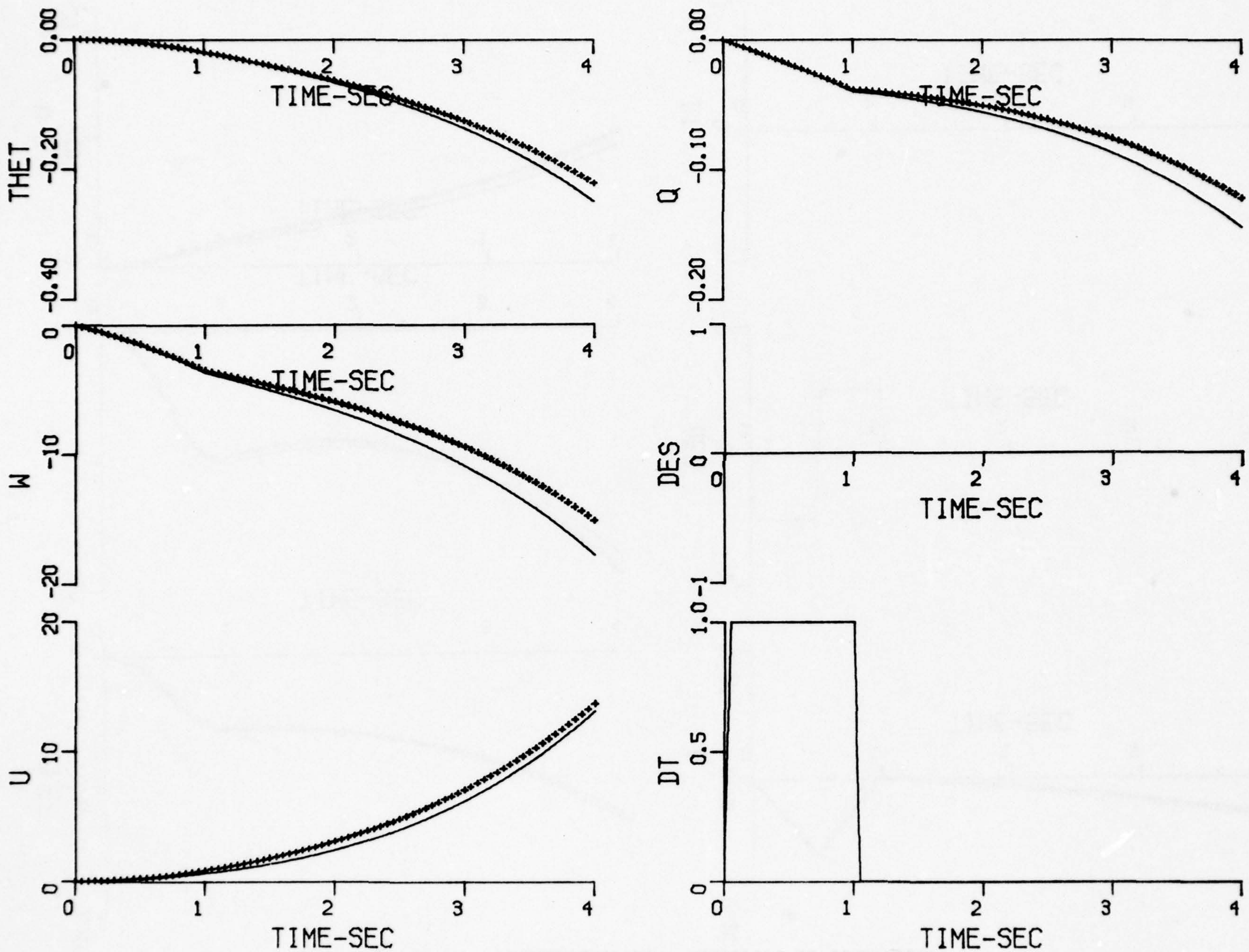


Figure I-4 (Cont) LONGITUDINAL TIME HISTORIES OF SIMULATION
(V = 50 Kt, Θ_j = 81 deg, 1 inch δ_T PULSE)

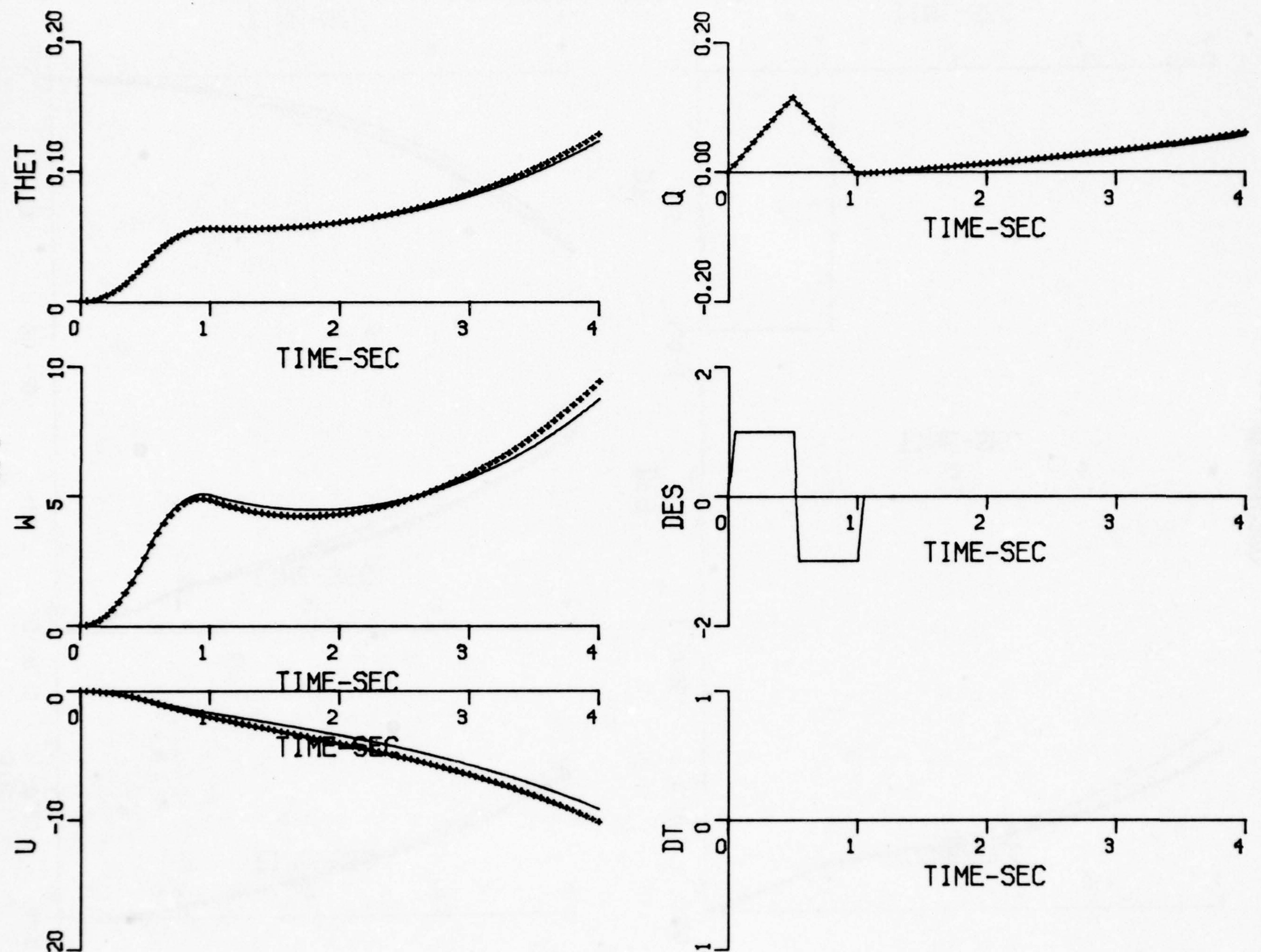


Figure I-4(Cont) LONGITUDINAL TIME HISTORIES OF SIMULATION (V = 65 Kt, θ_j = 81 deg, 1 inch δ_{ES} DOUBLET)

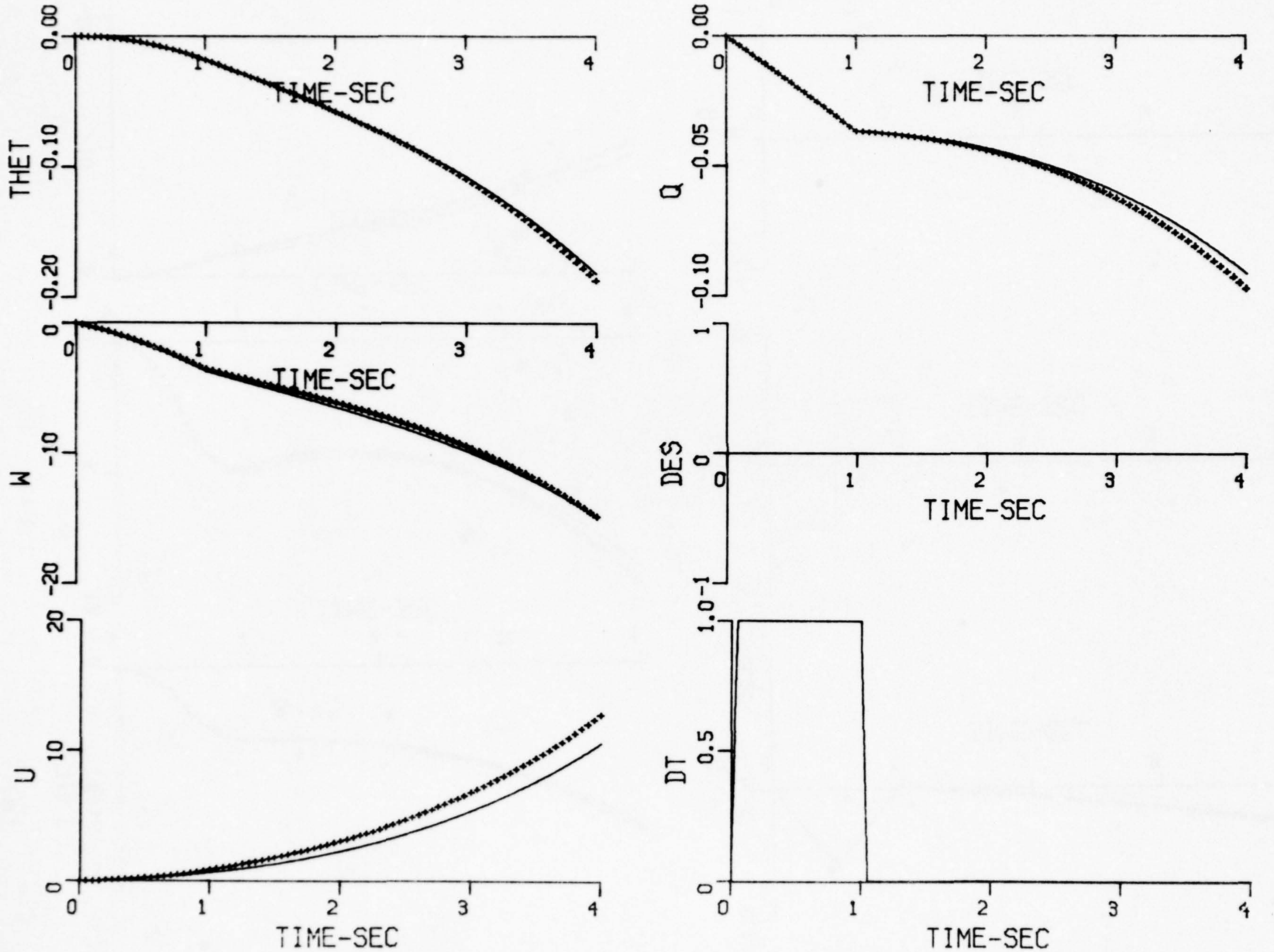


Figure I-4 (Cont) LONGITUDINAL TIME HISTORIES OF SIMULATION
(V = 65 Kt, θ_j = 81 deg, 1 inch δ_T PULSE)

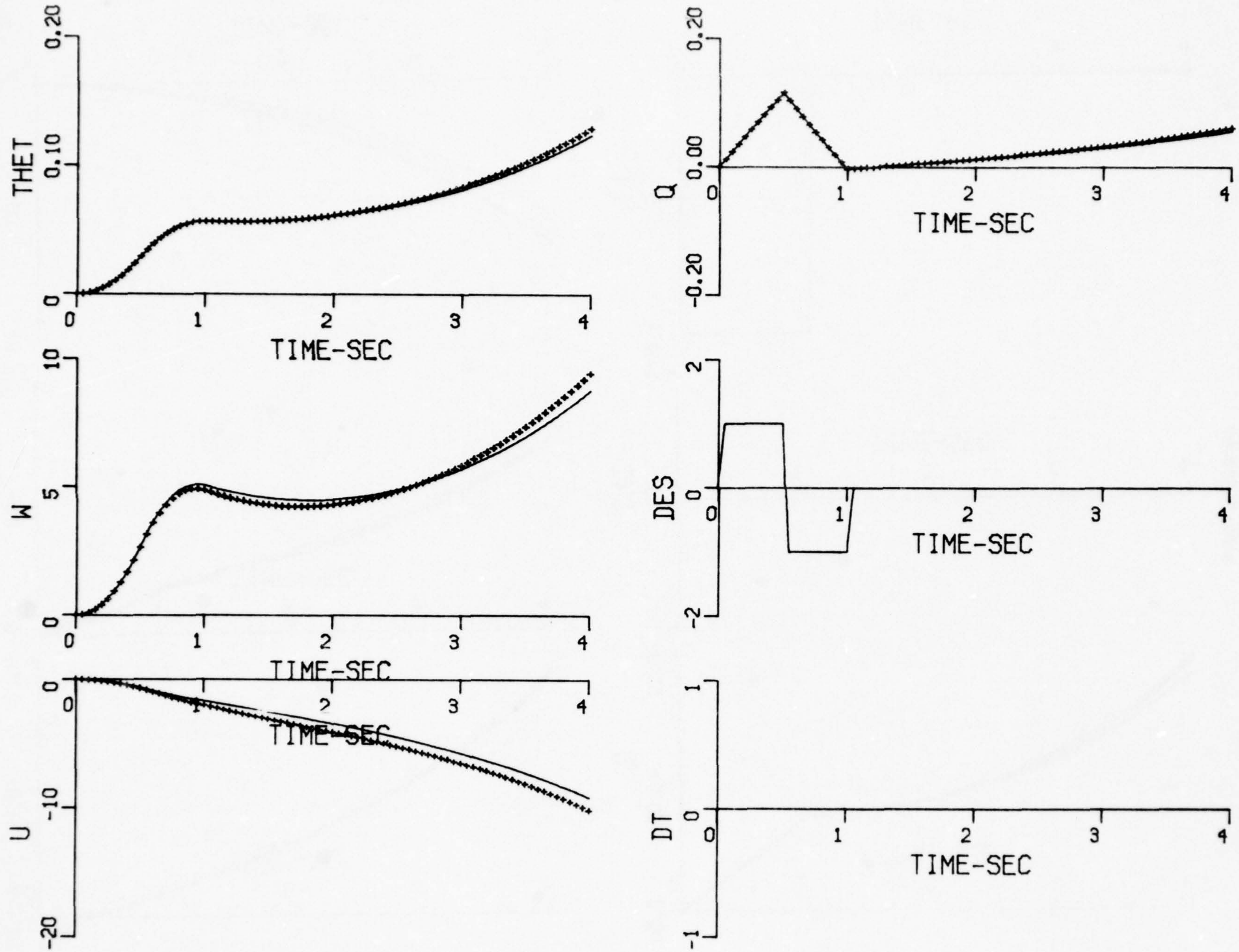


Figure I-4(Cont) LONGITUDINAL TIME HISTORIES OF SIMULATION (V = 65 Kt, θ_j = 69 deg, 1 inch δ_{ES} DOUBLET)

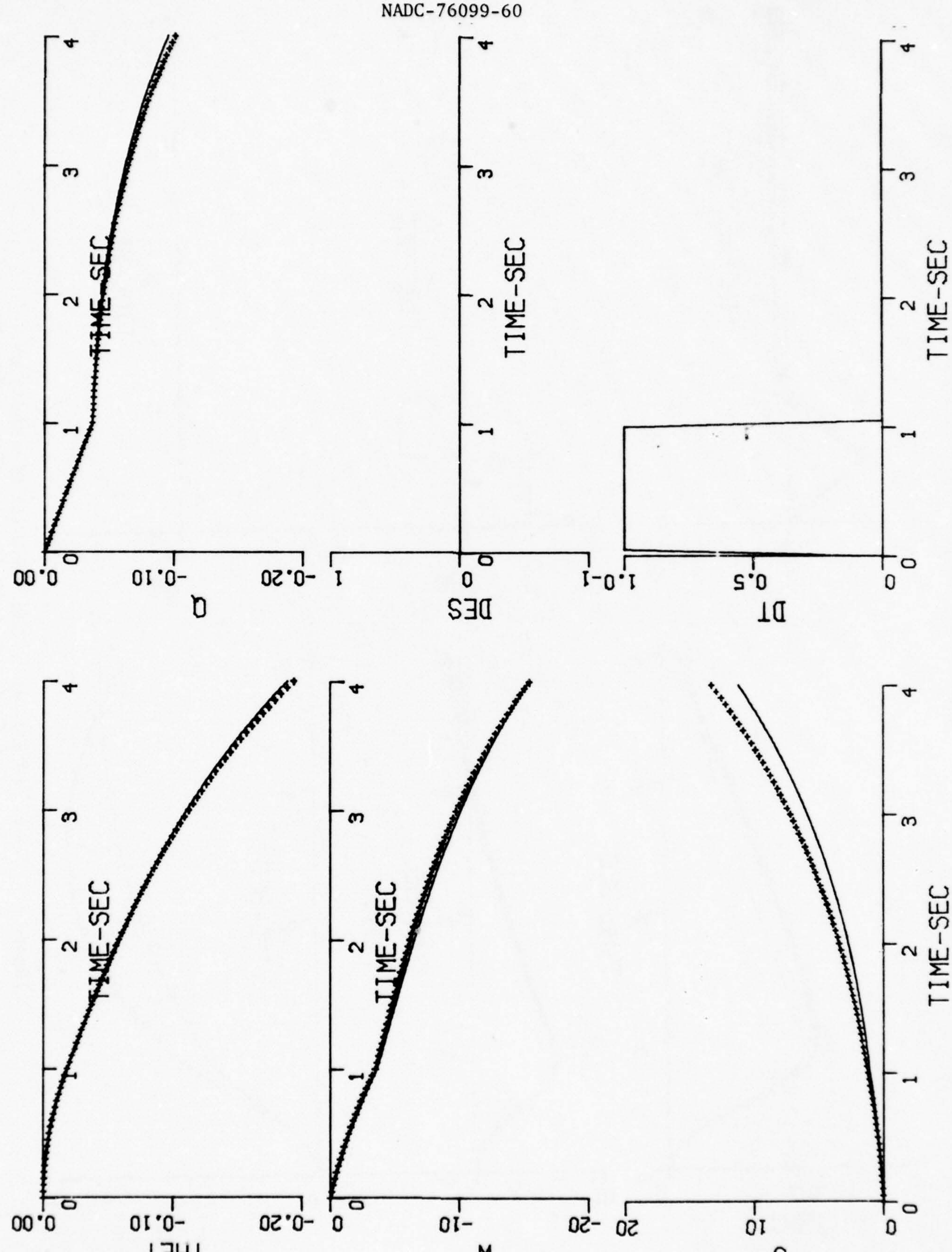


Figure I-4(Cont) LONGITUDINAL TIME HISTORIES OF SIMULATION (V = 65 Kt, θ_j = 69 deg, 1 inch δ_T PULSE)

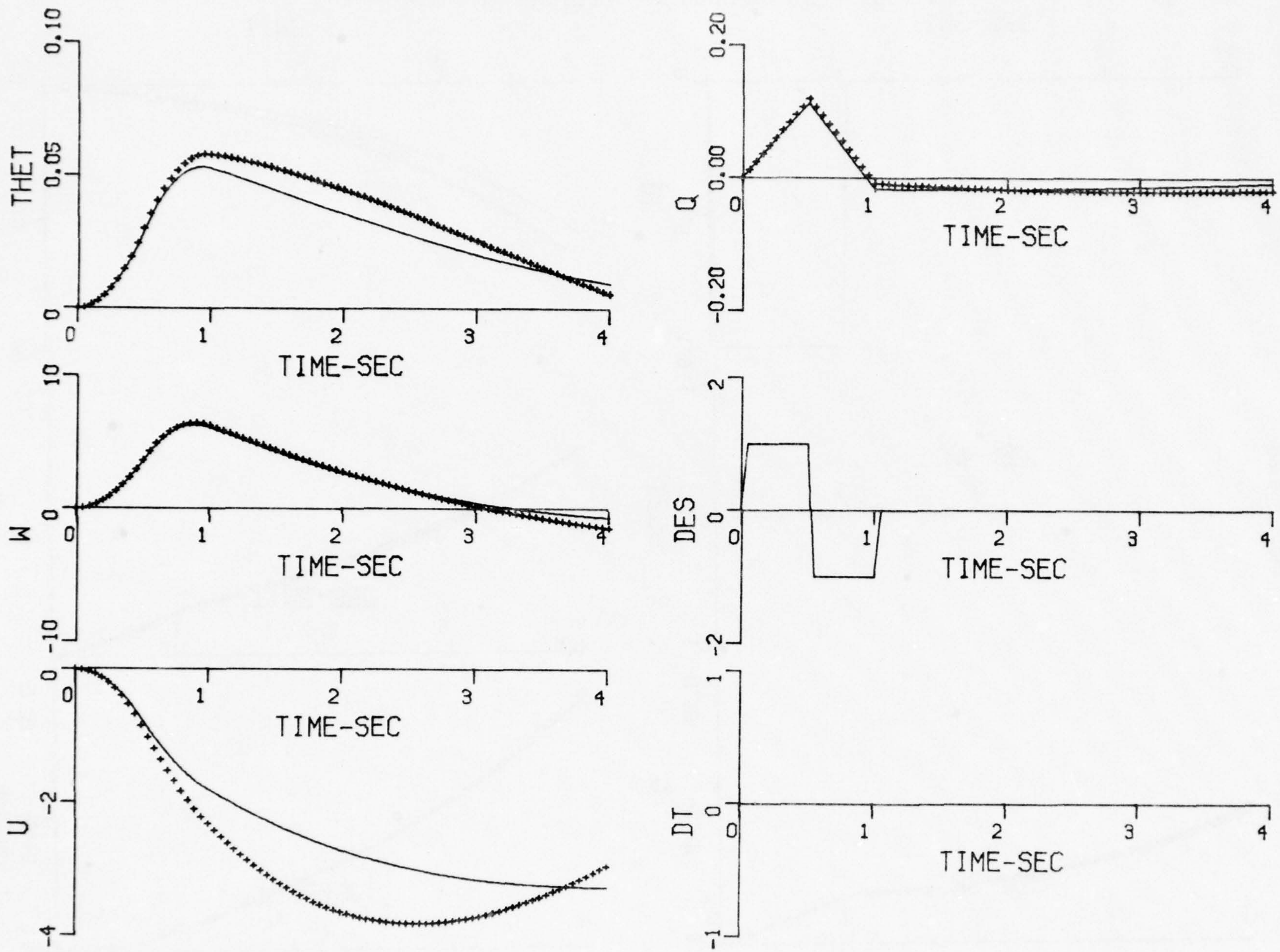


Figure I-4 (Cont) LONGITUDINAL TIME HISTORIES OF SIMULATION
(V = 80 Kt, Θ_j = 81 deg, 1 inch δ_{ES} DOUBLET)

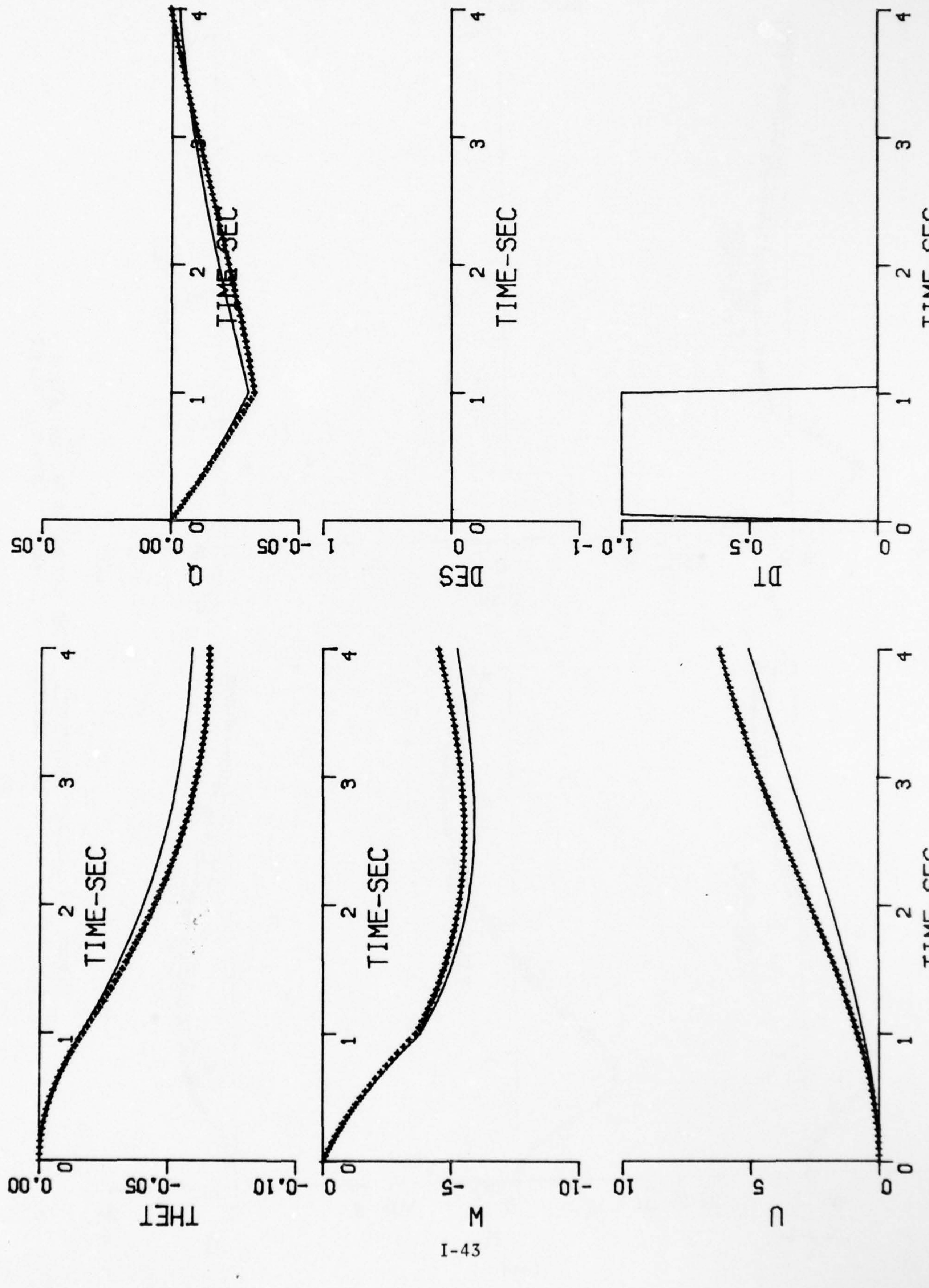


Figure I-4(Cont) LONGITUDINAL TIME HISTORIES OF SIMULATION
(V = 80 Kt, θ_j = 81 deg, 1 inch δ_T PULSE)

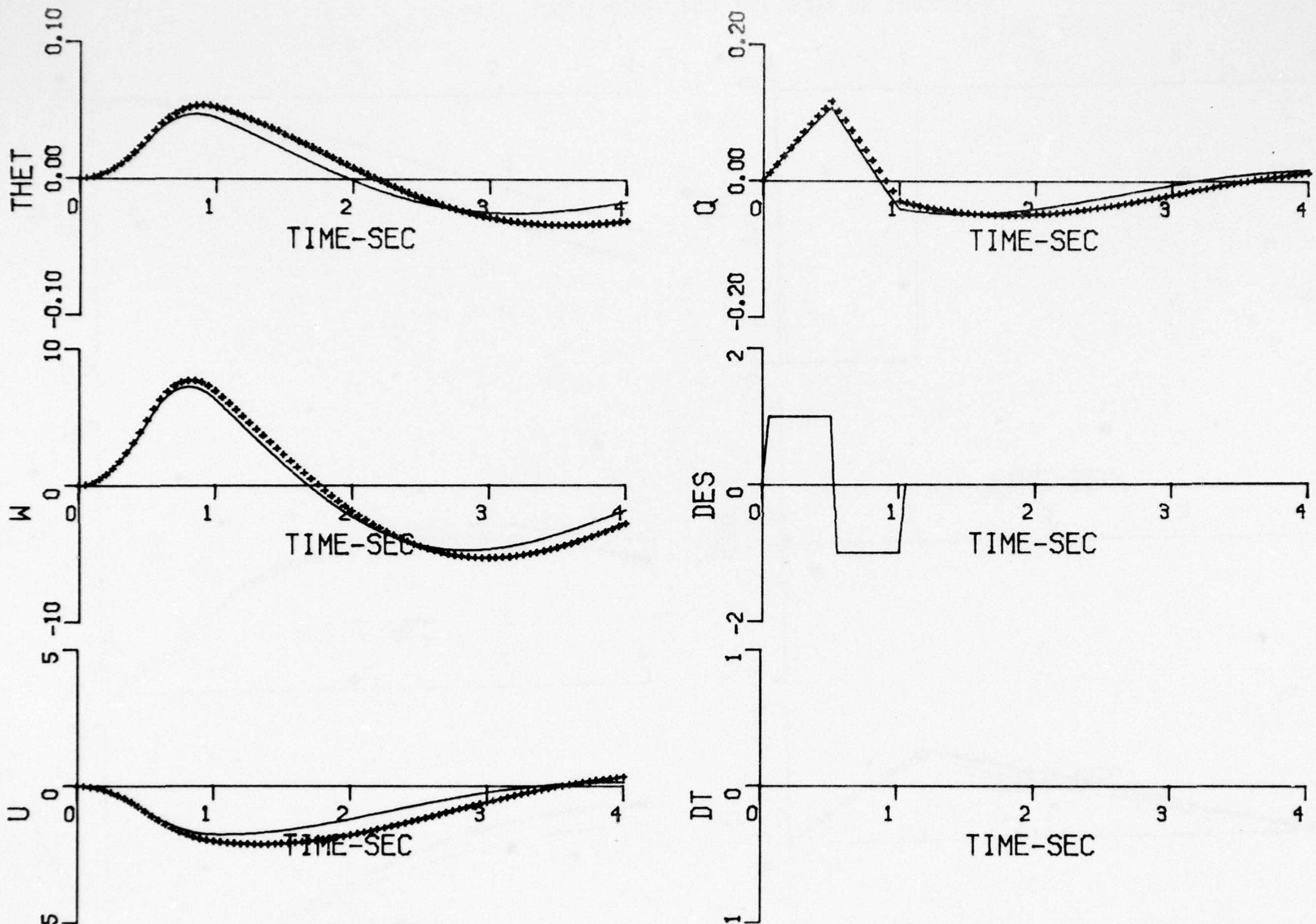


Figure I-4 (Cont) LONGITUDINAL TIME HISTORIES OF SIMULATION
(V = 105 Kt, θ_j = 81 deg, 1 inch δ_{ES} DOUBLET)

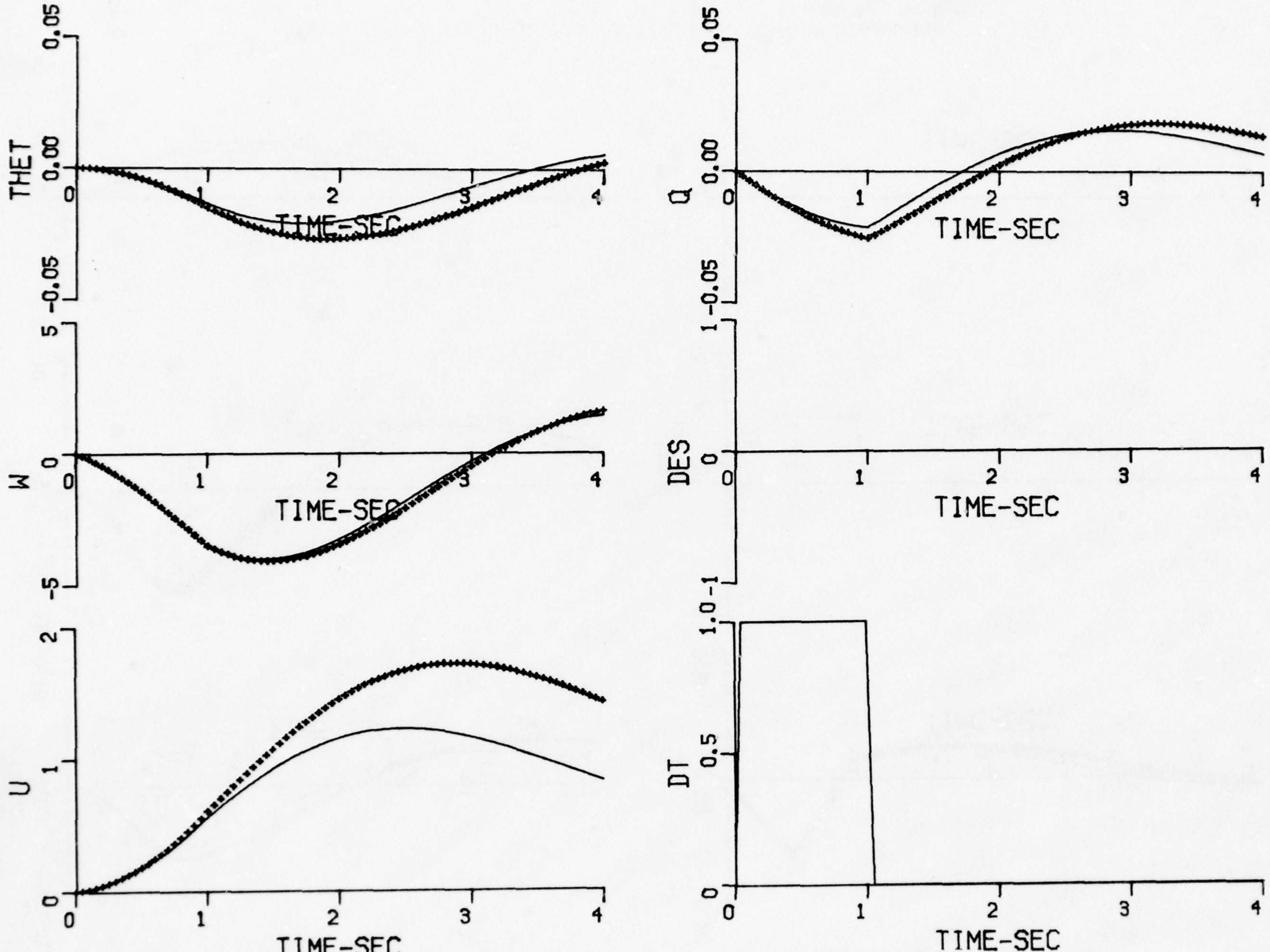


Figure I-4(Cont) LONGITUDINAL TIME HISTORIES OF SIMULATION
(V = 105 Kt, θ_j = 81 deg, 1 inch δ_T PULSE)

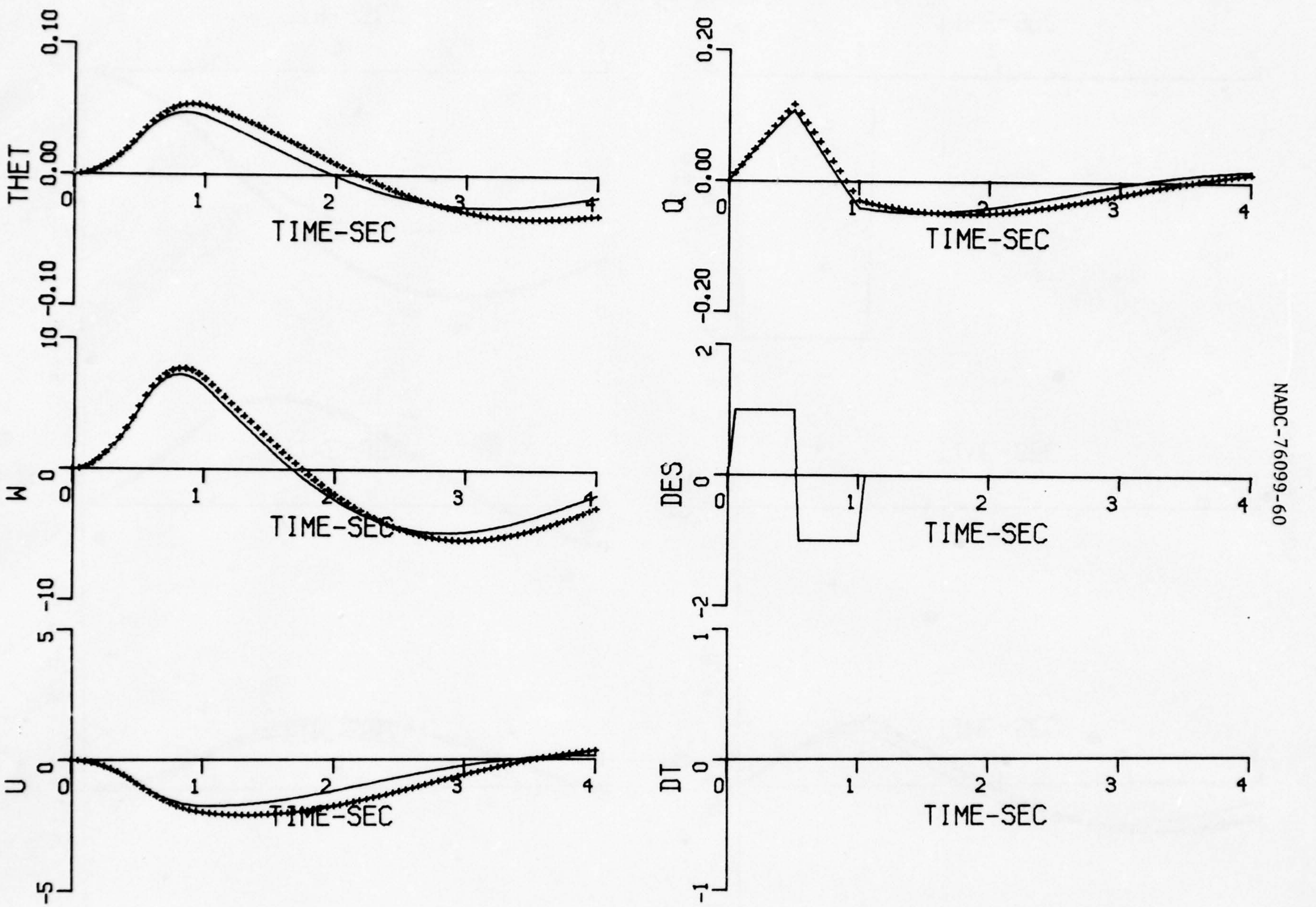


Figure I-4 (Cont) LONGITUDINAL TIME HISTORIES OF SIMULATION
(V = 105 Kt, Θ_j = 62 deg, 1 inch δ_{ES} DOUBLET)

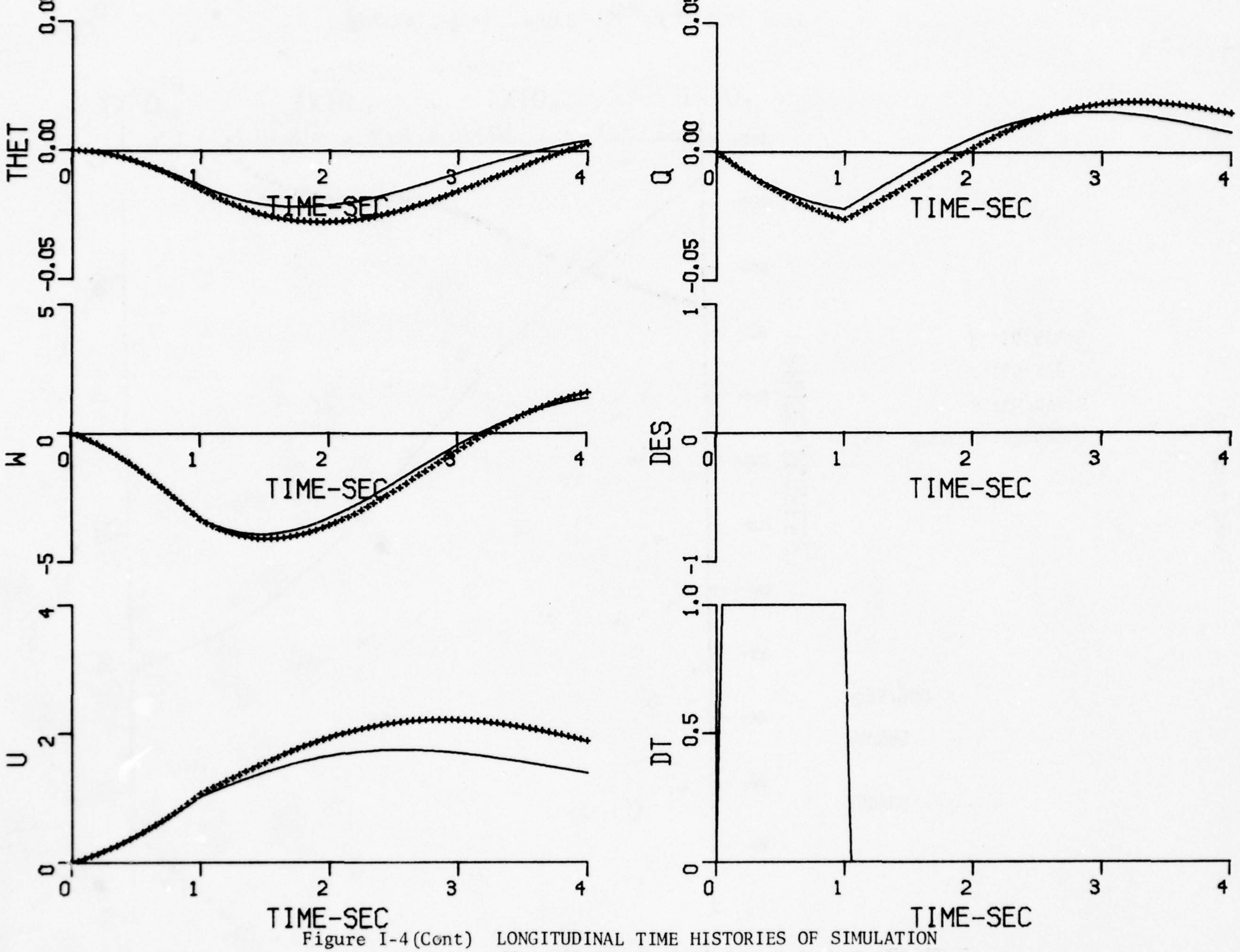


Figure I-4 (Cont) LONGITUDINAL TIME HISTORIES OF SIMULATION
(V = 105 Kt, θ_j = 62 deg, 1 inch δ_T PULSE)

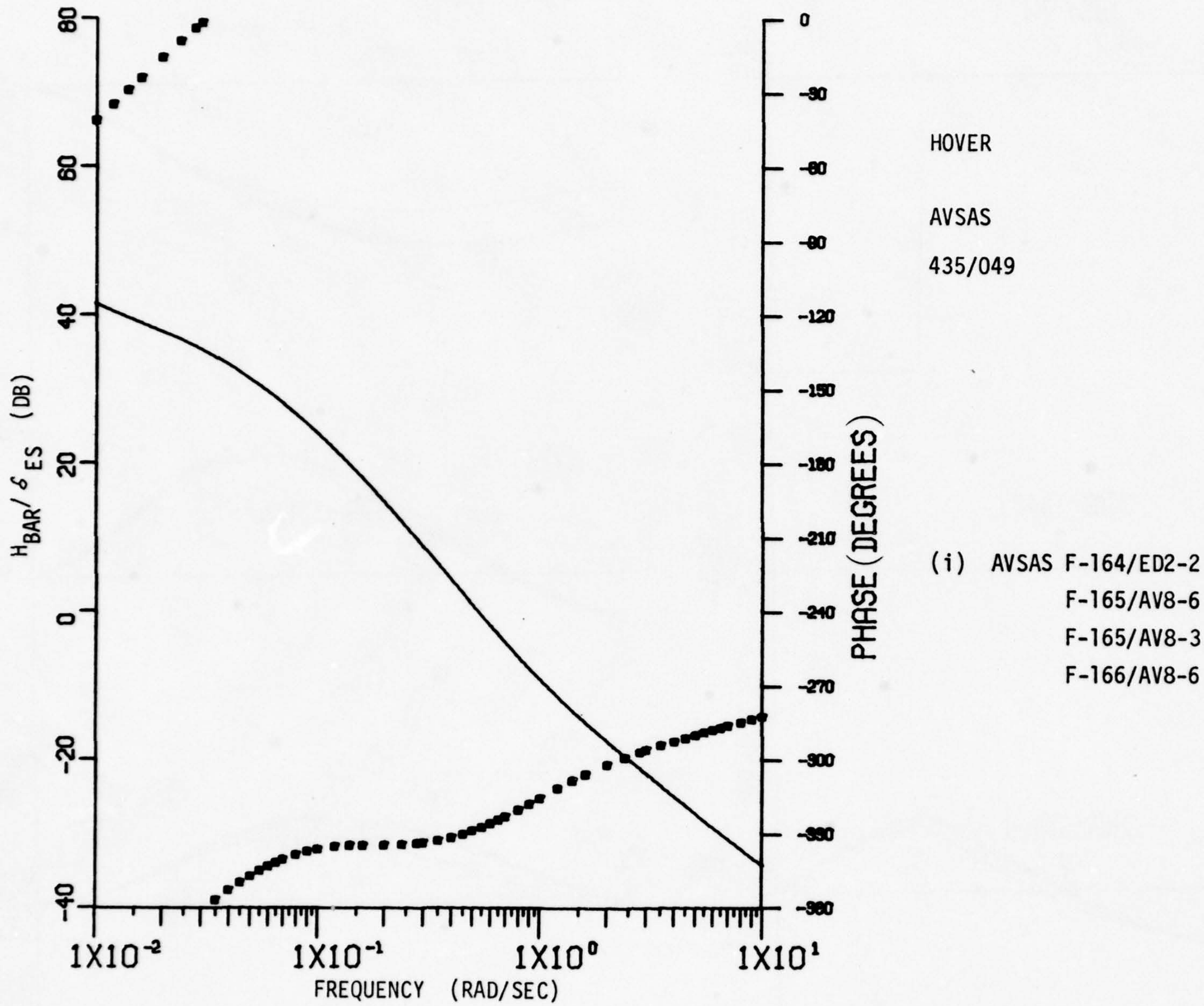
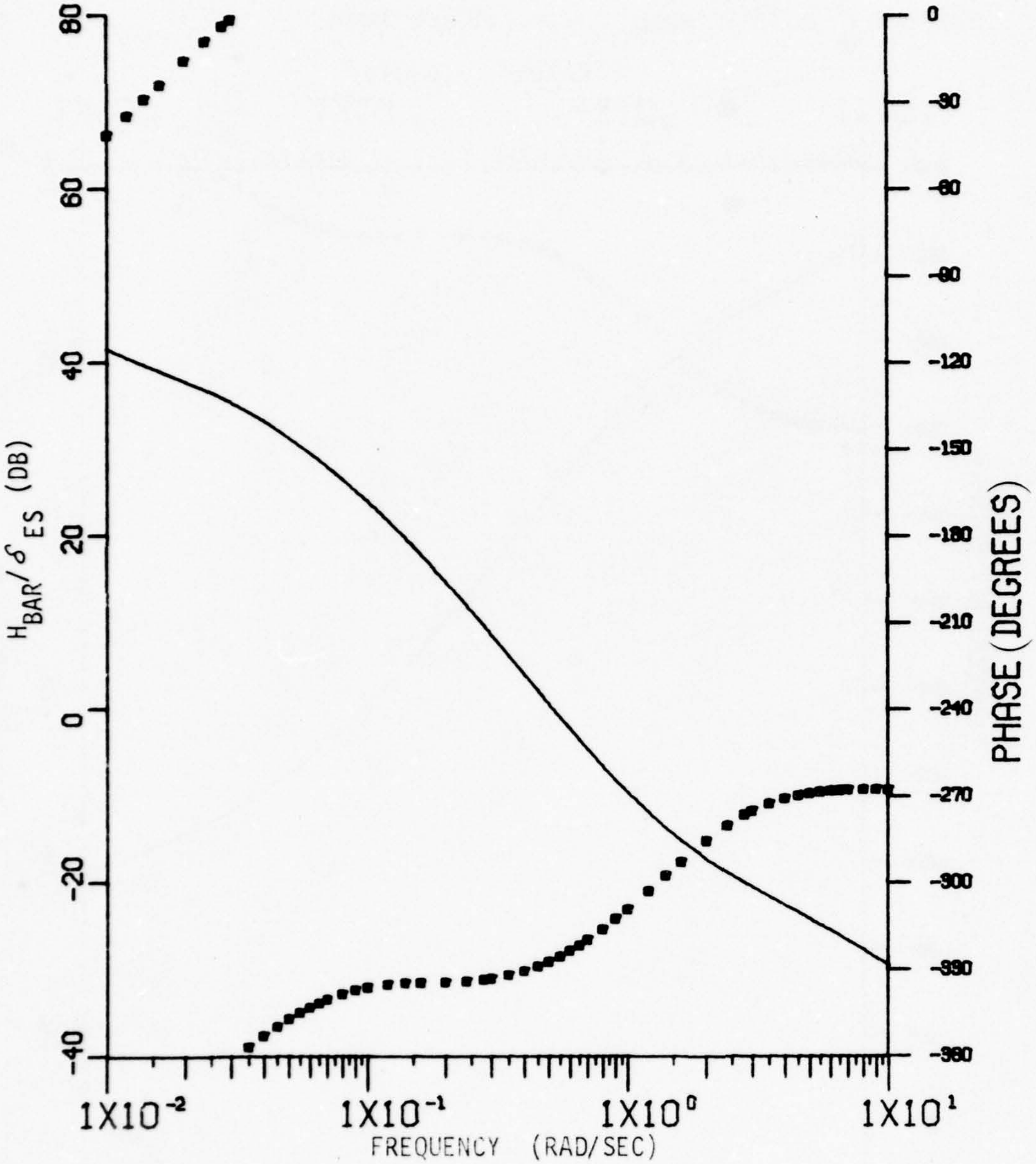


Figure I-5(a) HOVER, H_{BAR}/δ_{ES} BODE PLOT



AVSAS

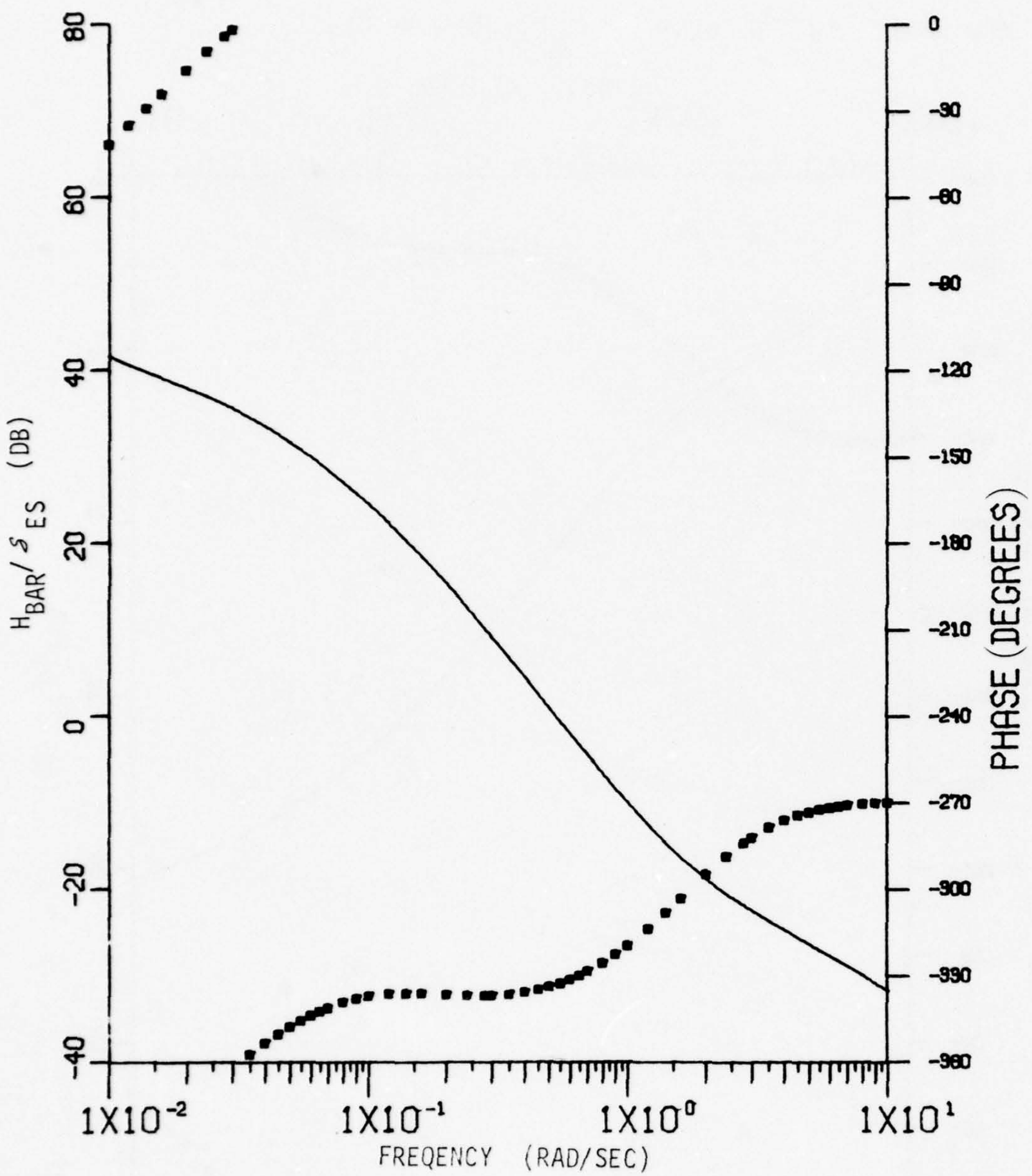
435/103

(ii) AVSAS F-178/ED2-2

F-179/AV8-6

F-181/ED2-2

Figure I-5(a)(Cont) HOVER, H_{BAR}/δ_{ES} BODE PLOT



2.0 RCAH

354/077

(iii) RCAH 2 F-169/AV8-3

Figure I-5(a)(Cont) HOVER, H_{BAR}/δ_{ES} BODE PLOT

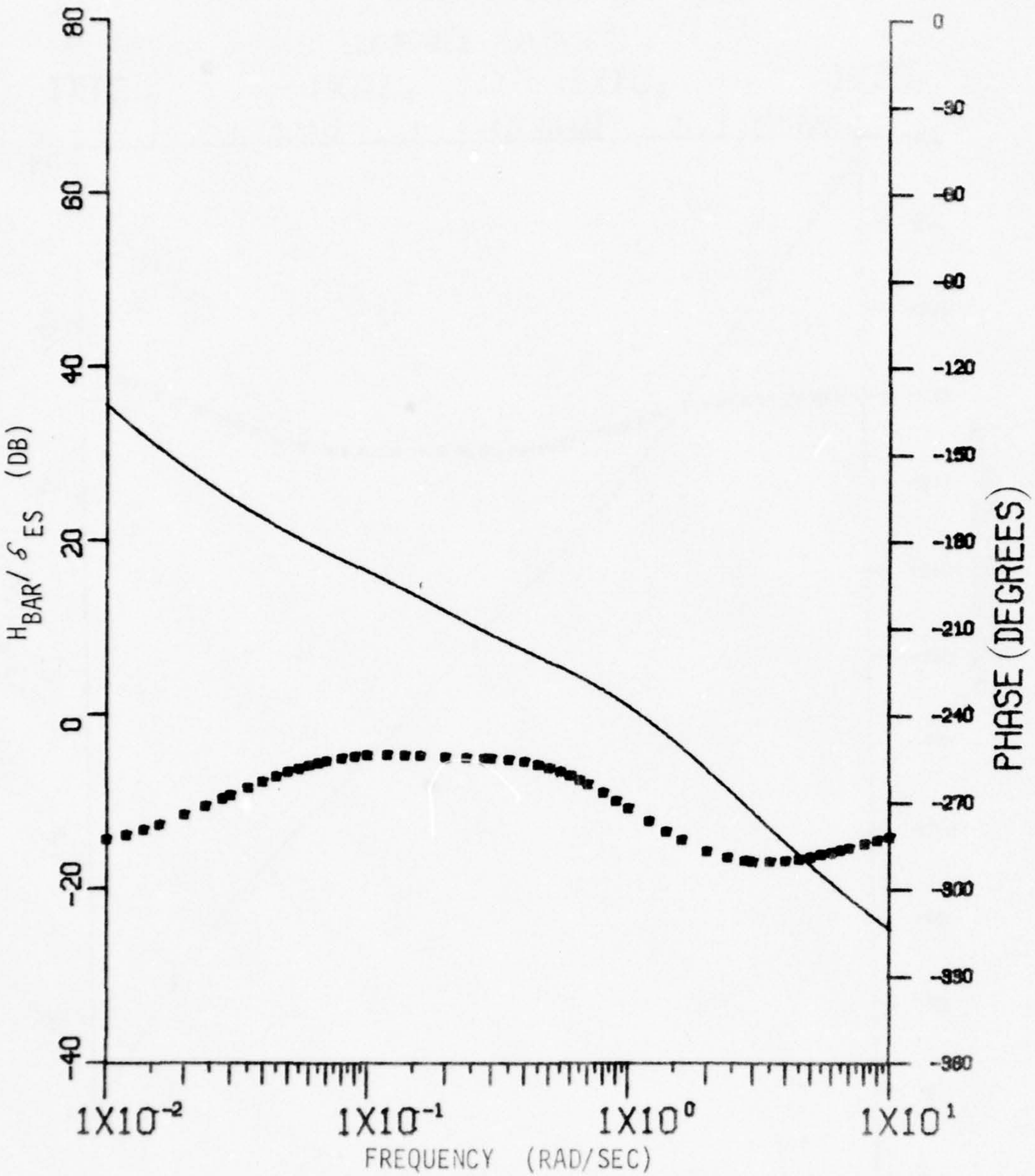


Figure I-5(a)(Cont) HOVER, H_{BAR}/δ_{ES} BODE PLOT

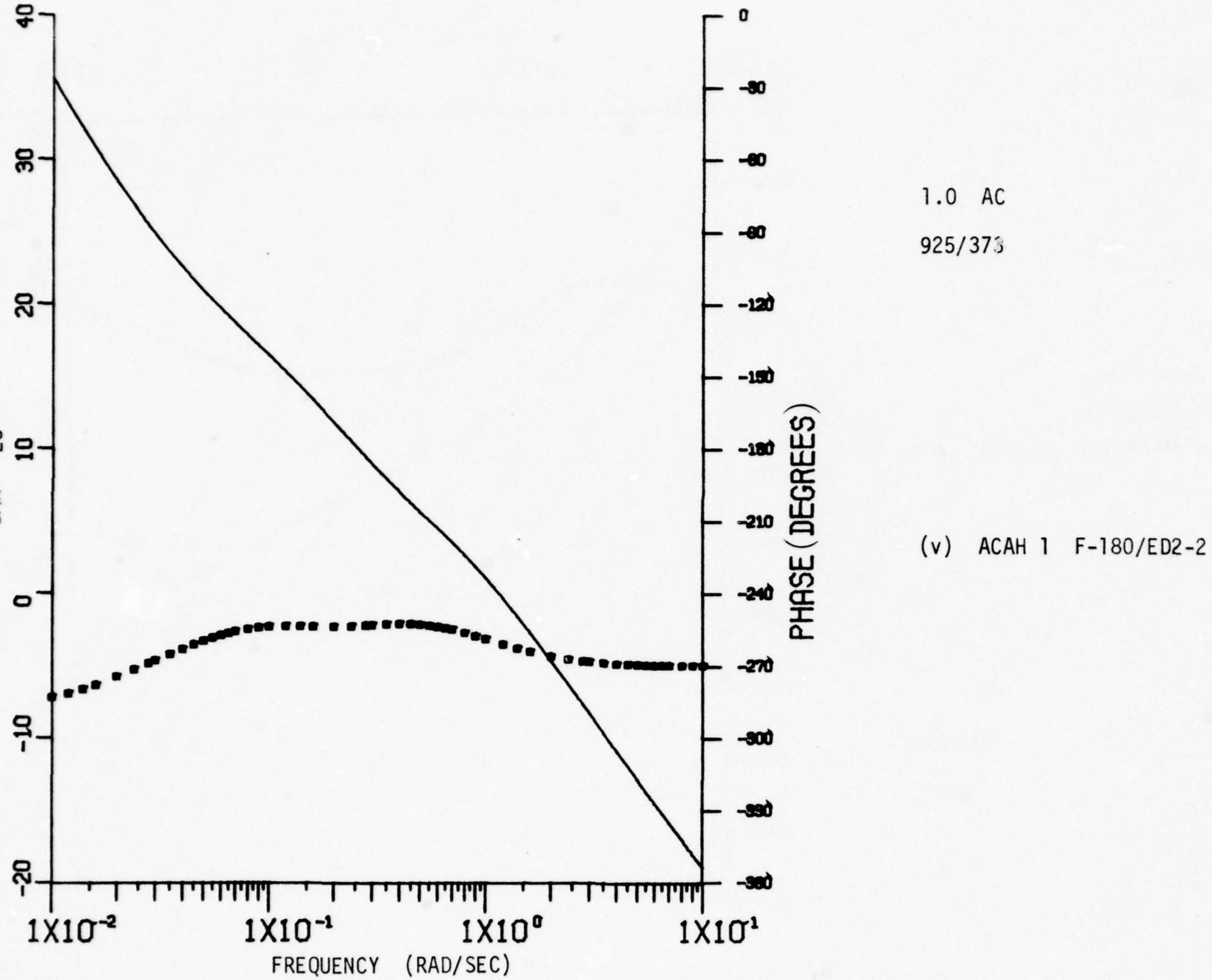


Figure I-5(a)(Cont) HOVER, H_{BAR}/δ_{ES} BODE PLOT

1.5 AC

700/220

(vi) ACAH 1.5 F-179/AV8-3

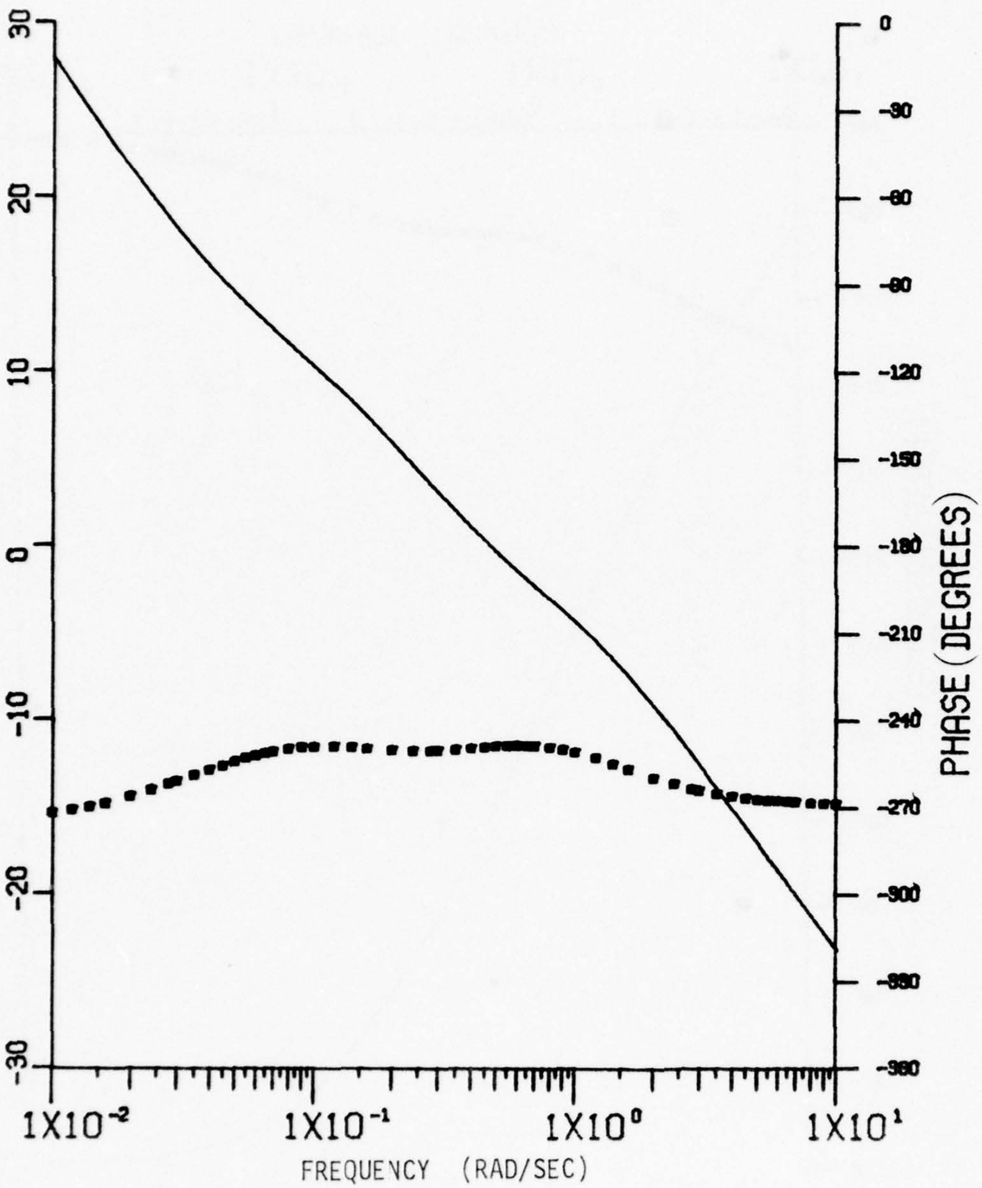


Figure I-5(a)(Cont) HOVER, H_{BAR}/δ_{ES} BODE PLOT

65 Knots

(i) AVSAS F-164/ED2-2
F-165/AV8-6
F-165/AV8-3
F-166/AV8-6

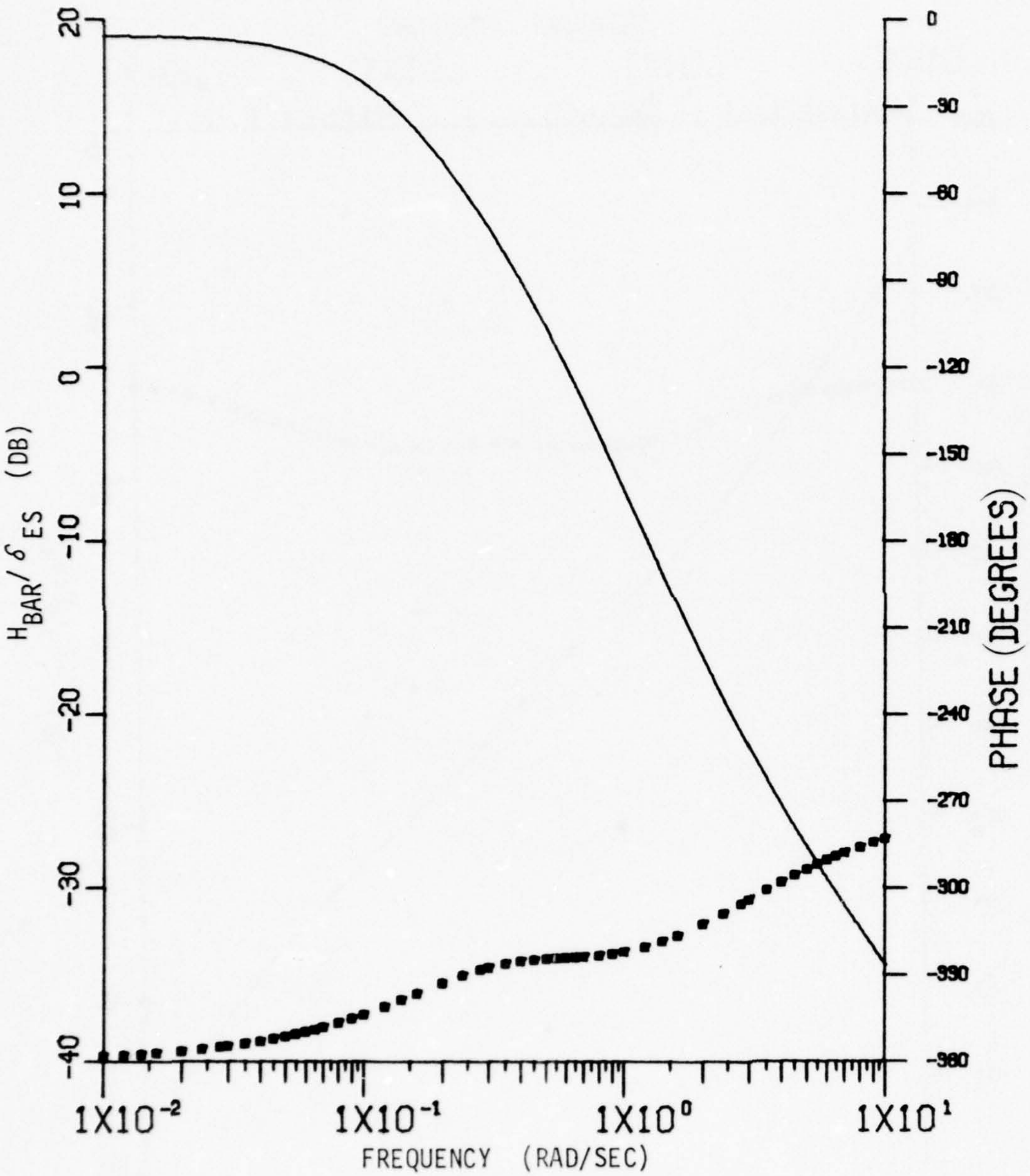


Figure I-5(b) 65 KNOTS H_{BAR}/δ_{ES} BODE PLOT

65 Knots

(ii) AVSAS F-178/ED2-2
F-179/AV8-6
F-181/ED2-2

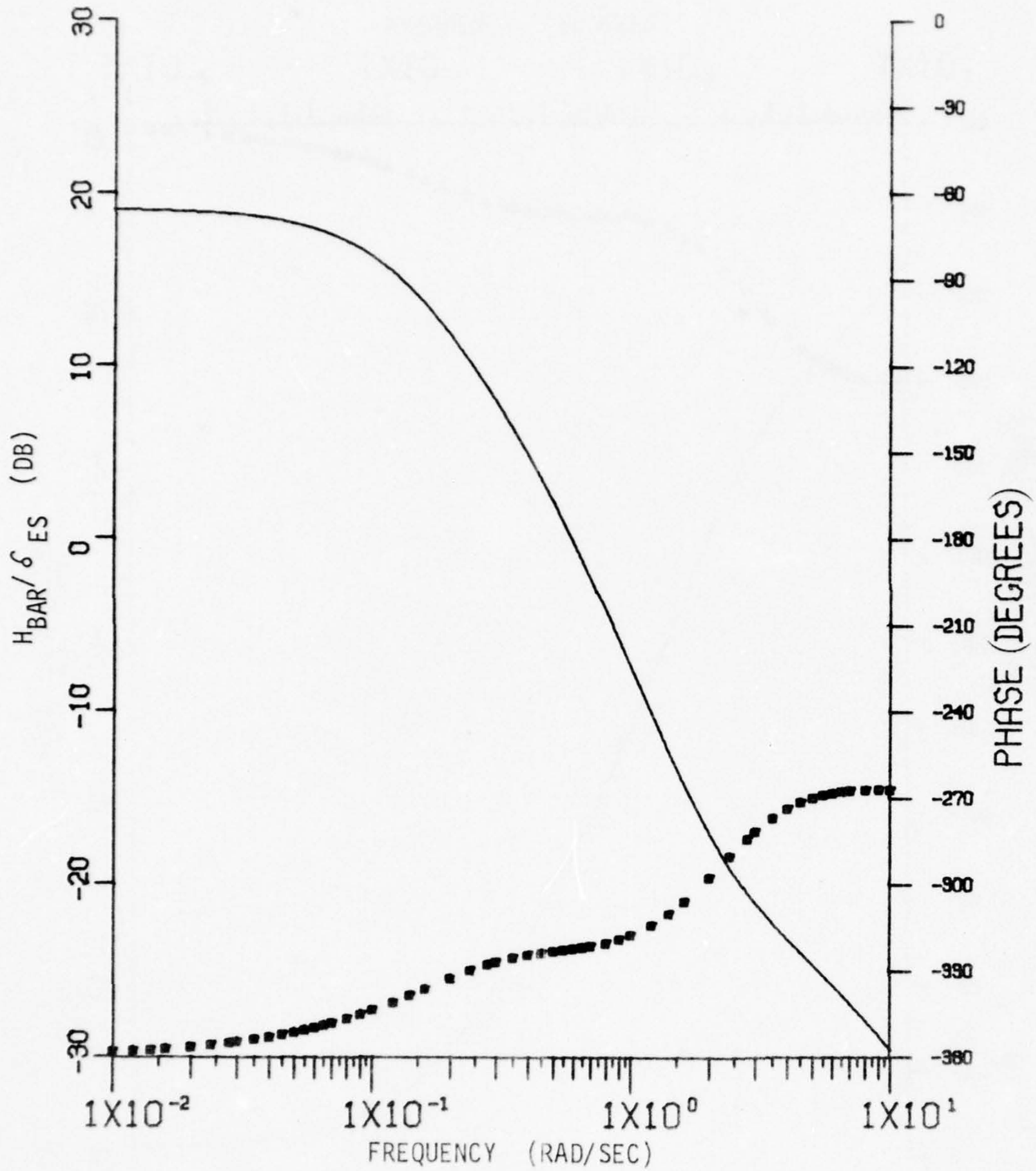


Figure I-5(b)(Cont) 65 KNOTS H_{BAR}/δ_{ES} BODE PLOT

65 Knots

(iii) RCAH 2 F-169/AV8-3

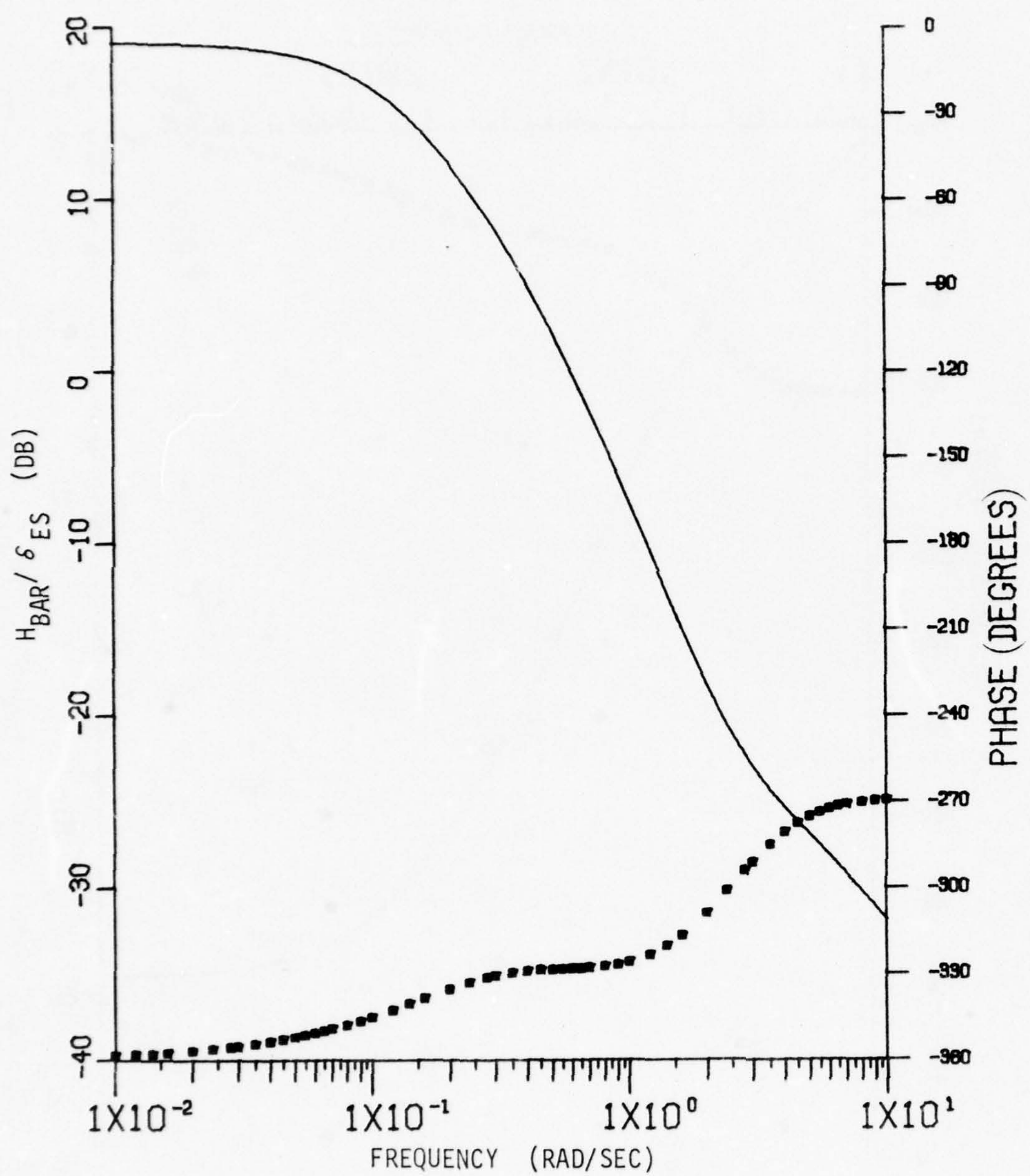


Figure I-5(b)(Cont) 65 KNOTS H_{BAR}/δ_{ES} BODE PLOT

65 Knots

(iv) ACAH 1 F-164/AV8-6

F-165/ED2-2

F-166/AV8-6

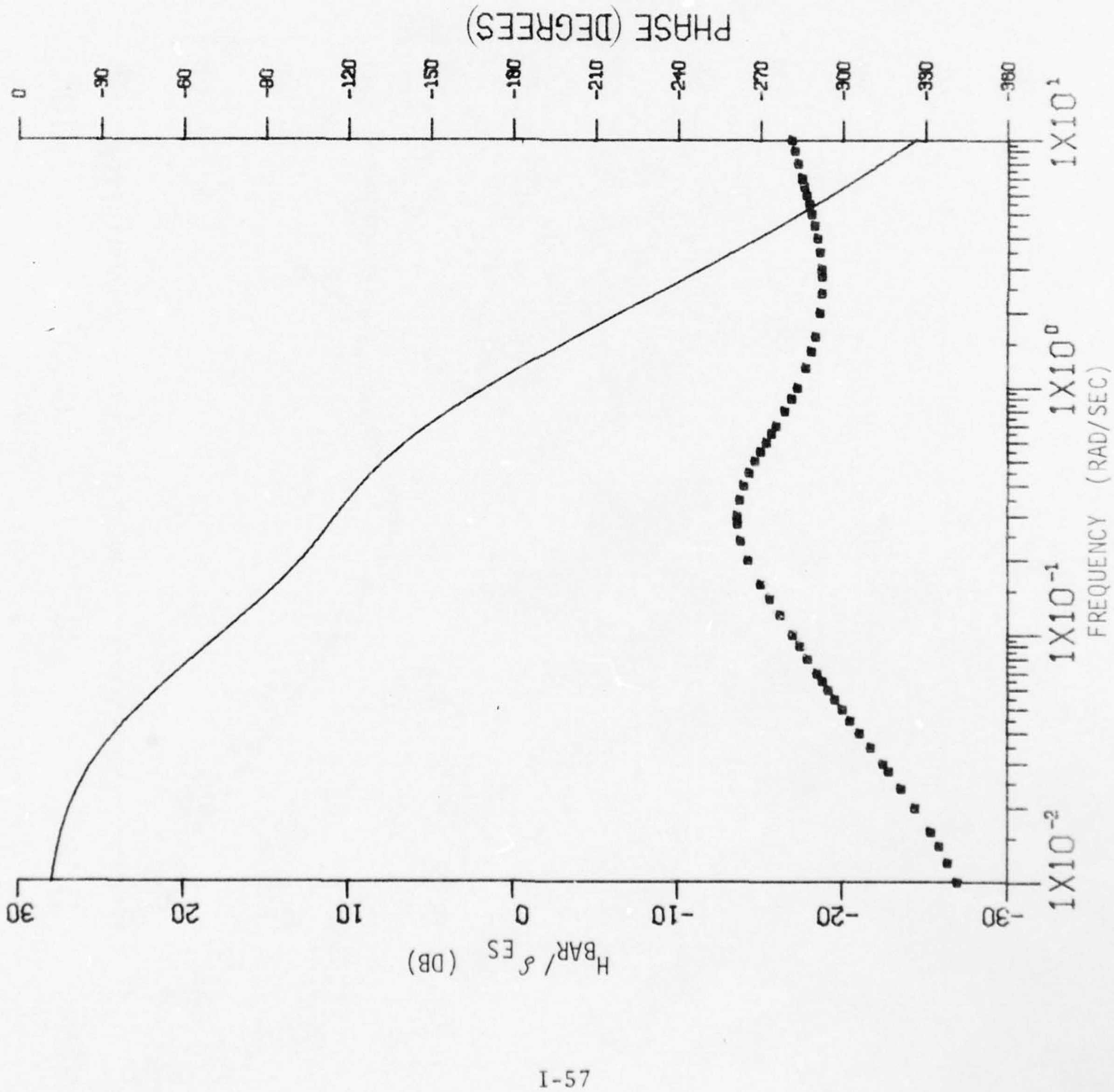


Figure I-5(b)(Cont) 65 KNOTS H_{BAR}/δ_{ES} BODE PLOT

65 Knots

(v) ACAH 1 F-180/ED2-2

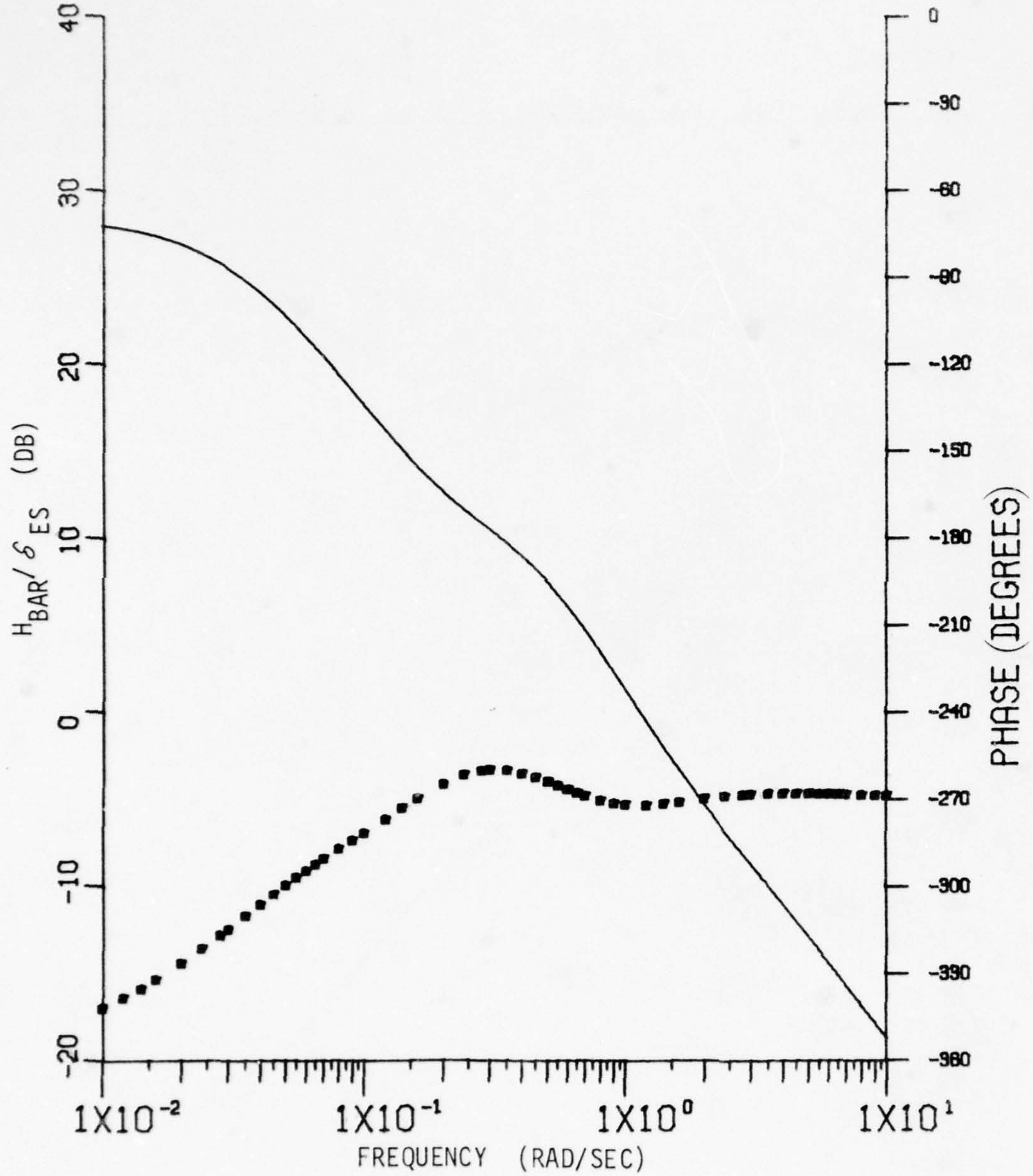


Figure I-5(b)(Cont) 65 KNOTS H_{BAR}/δ_{ES} BODE PLOT

65 Knots

(vi) ACAH 1.5 F-179/AV8-3

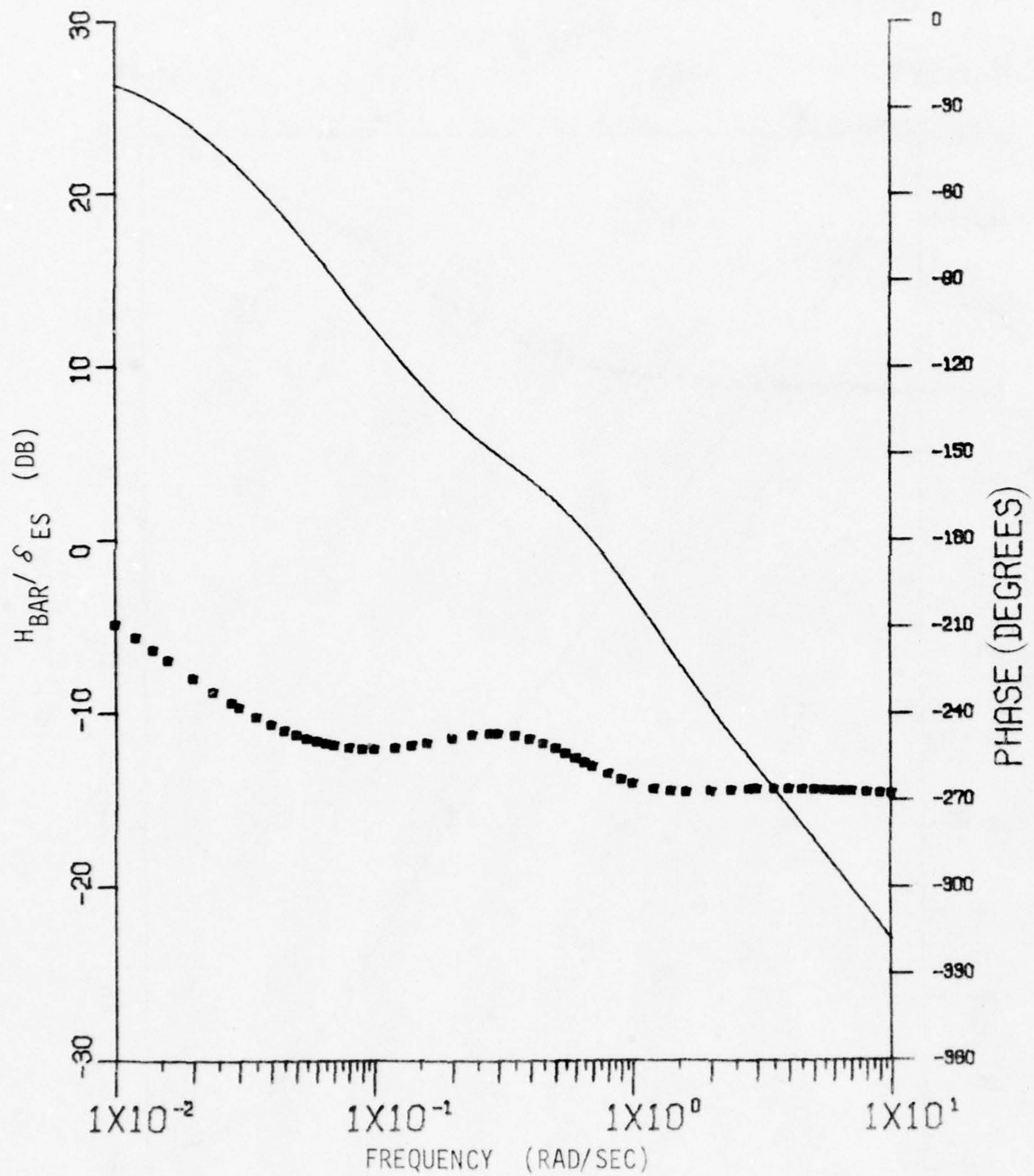


Figure I-5(b)(Cont) 65 KNOTS H_{BAR}/δ_{ES} BODE PLOT

HOVER

(i) AVSAS F-158/AV8-0
F-164/ED2-2
F-165/AV8-6
F-165/AV8-3
F-166/AV8-6
F-167/AV8-0
F-166/ED2-1

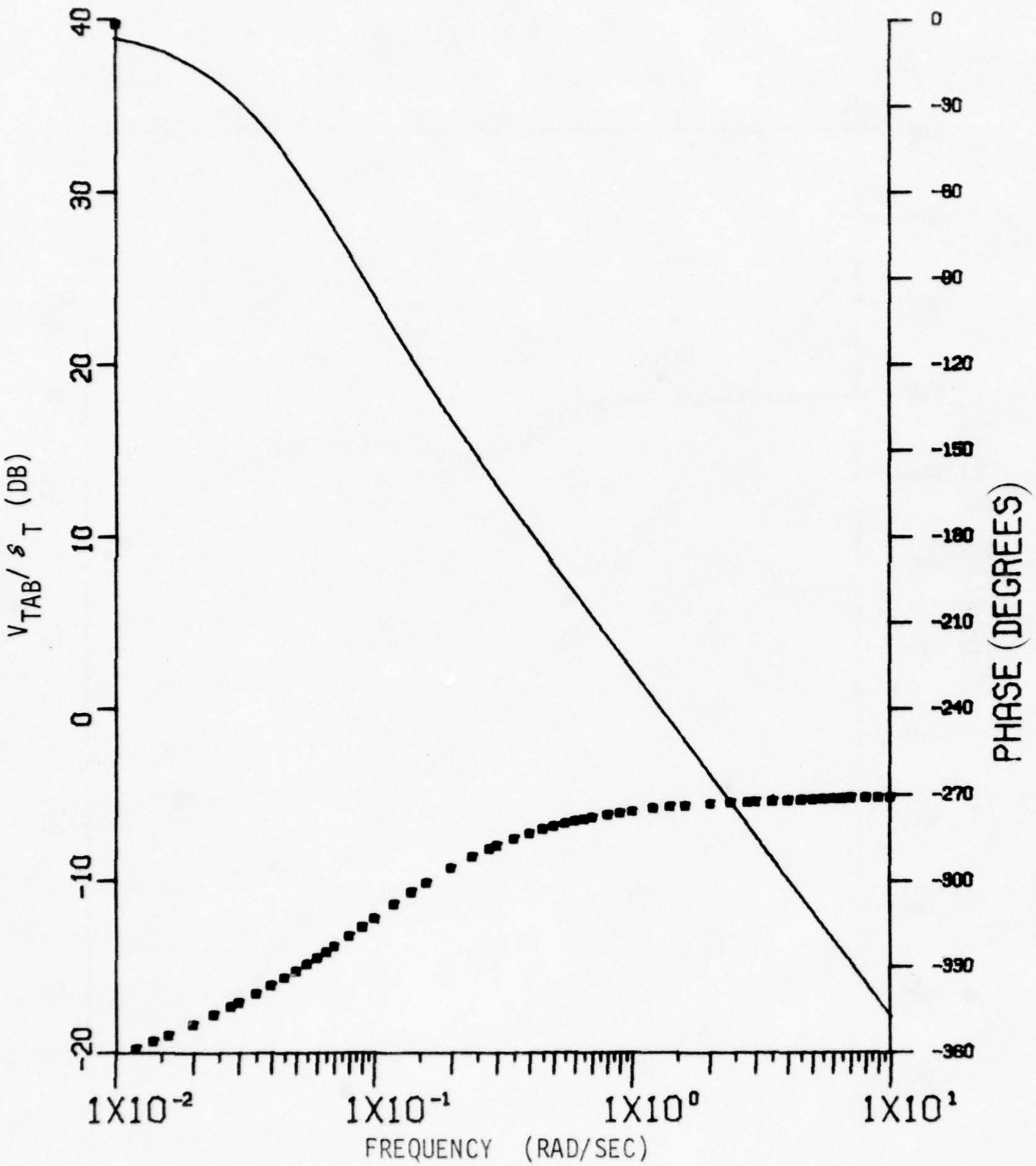


Figure I-6(a) HOVER V_{TAB}/δ_T BODE PLOT

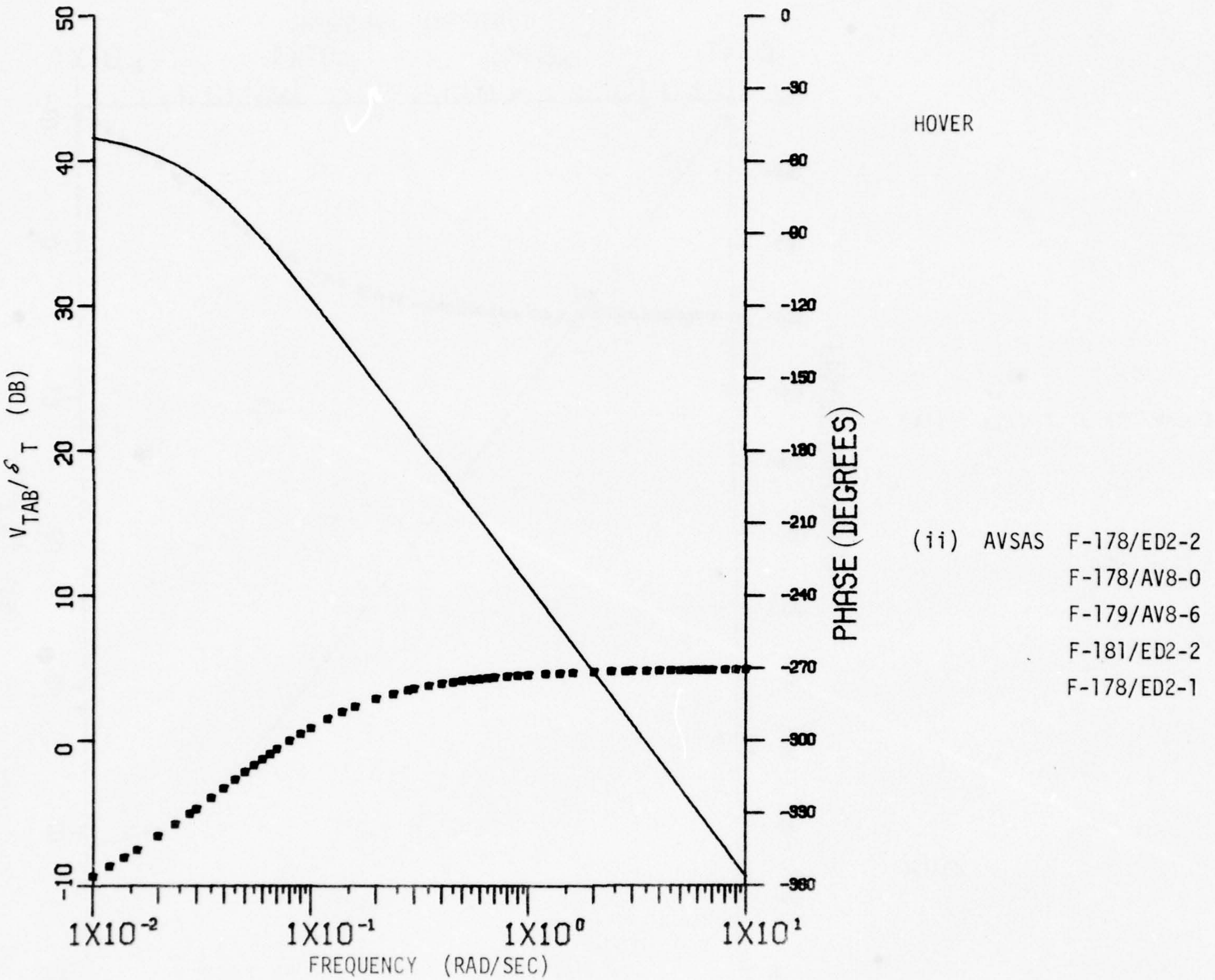


Figure I-6(a)(Cont) HOVER V_{TAB}/δ_T BODE PLOT

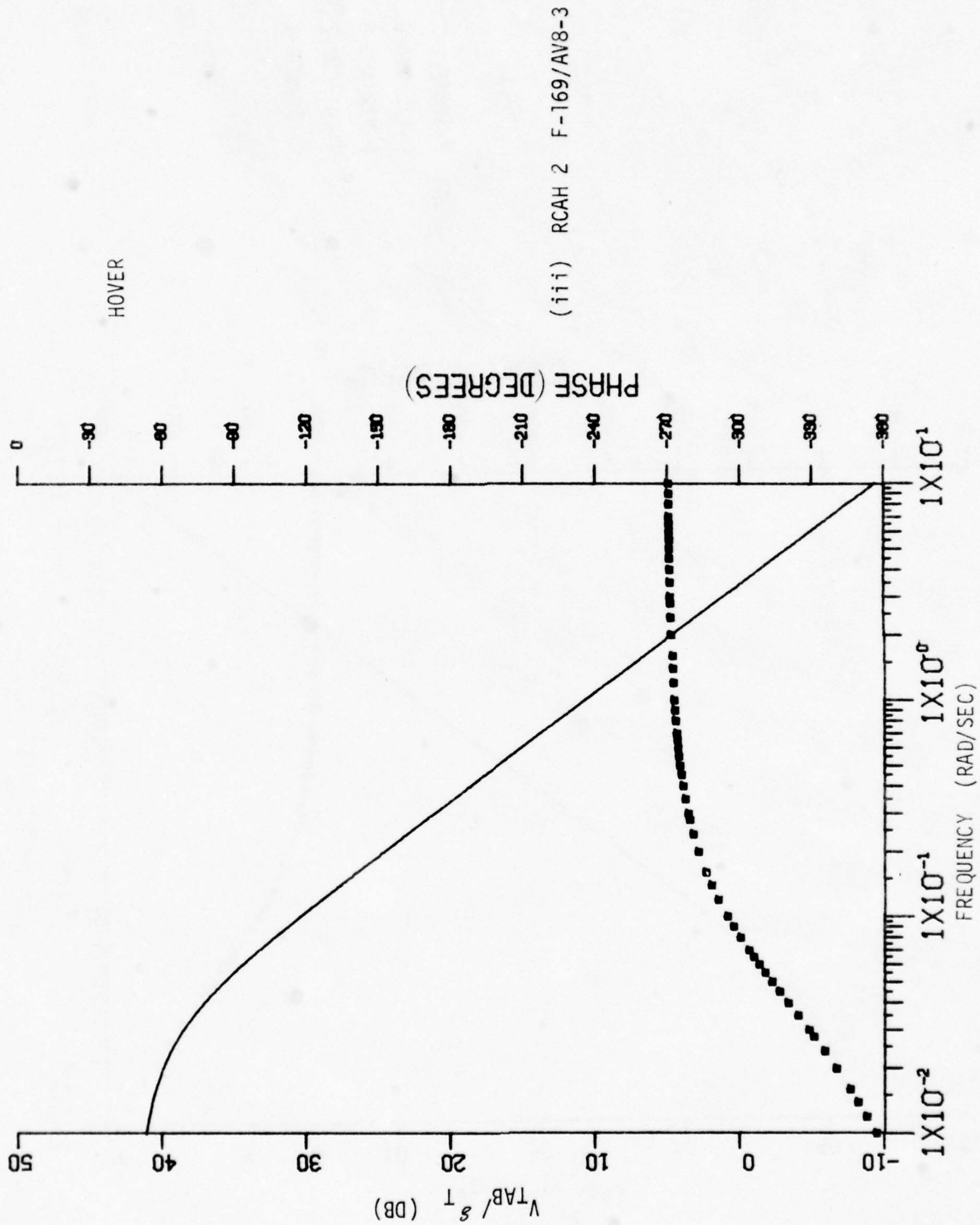


Figure I-6(a)(Cont) HOVER V_{TAB}/δ_T BODE PLOT

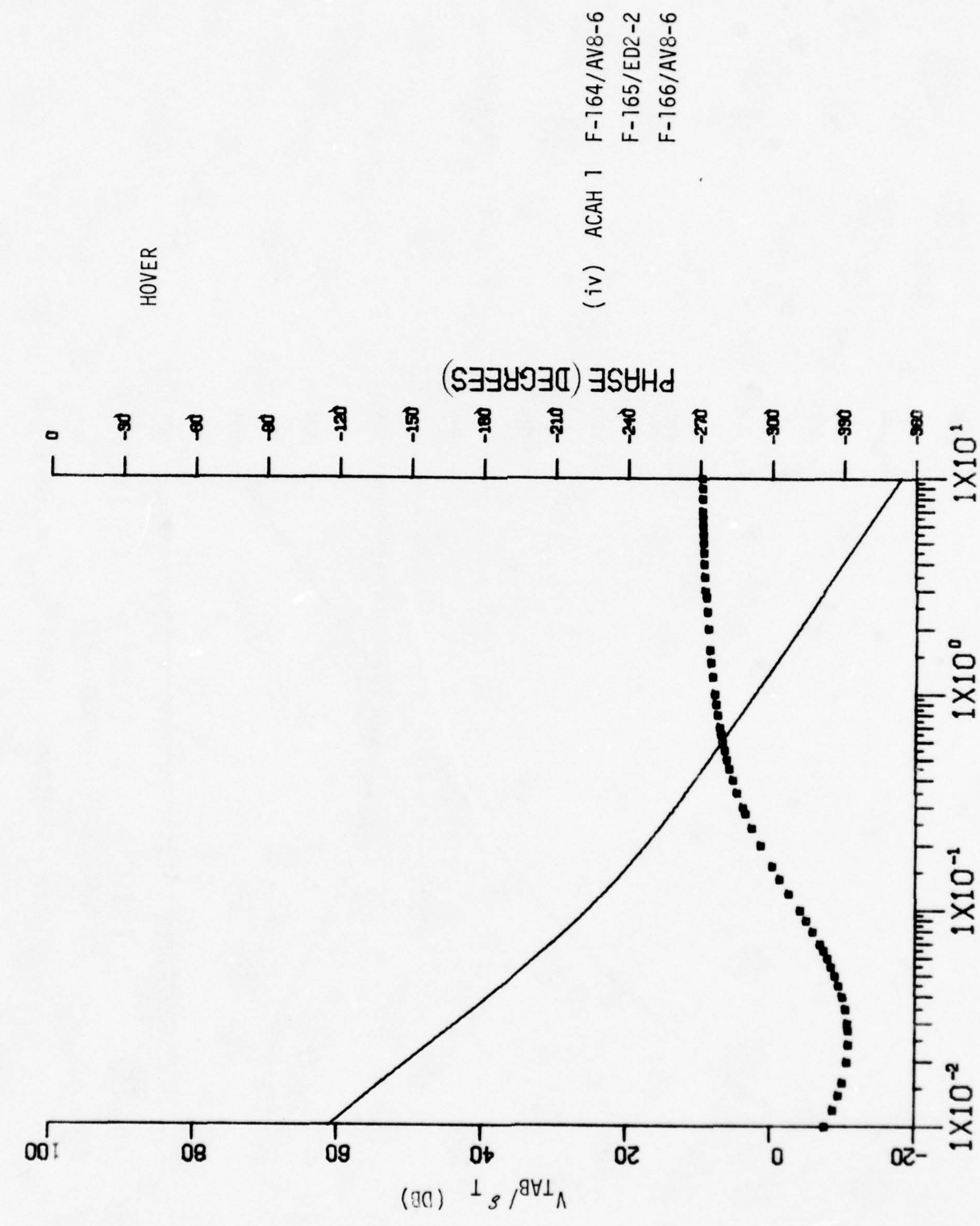


Figure I-6(a)(Cont) HOVER V_{TAB}/δ_T BODE PLOT

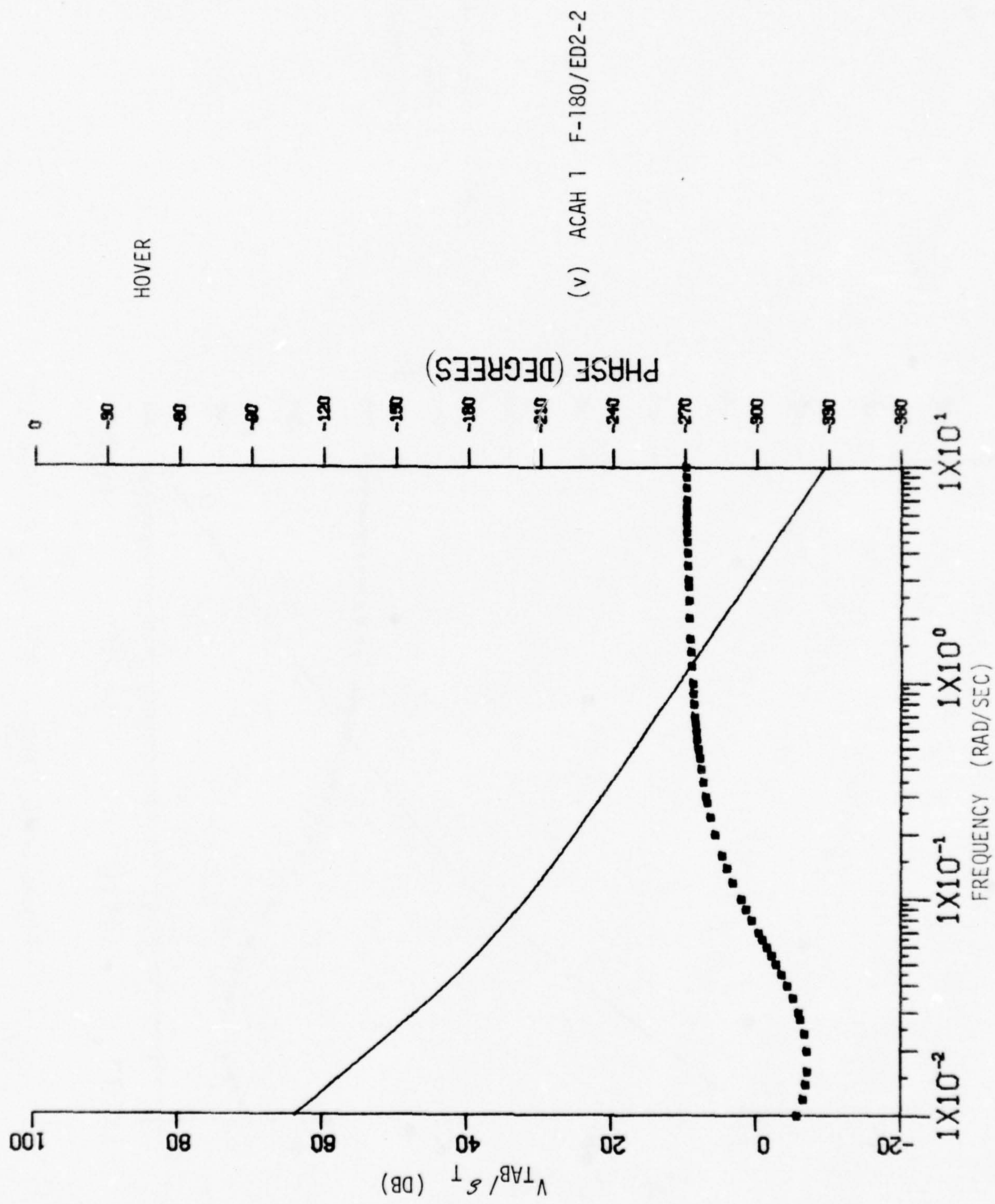


Figure I-6(a)(Cont) HOVER V_{TAB}/δ_T BODE PLOT

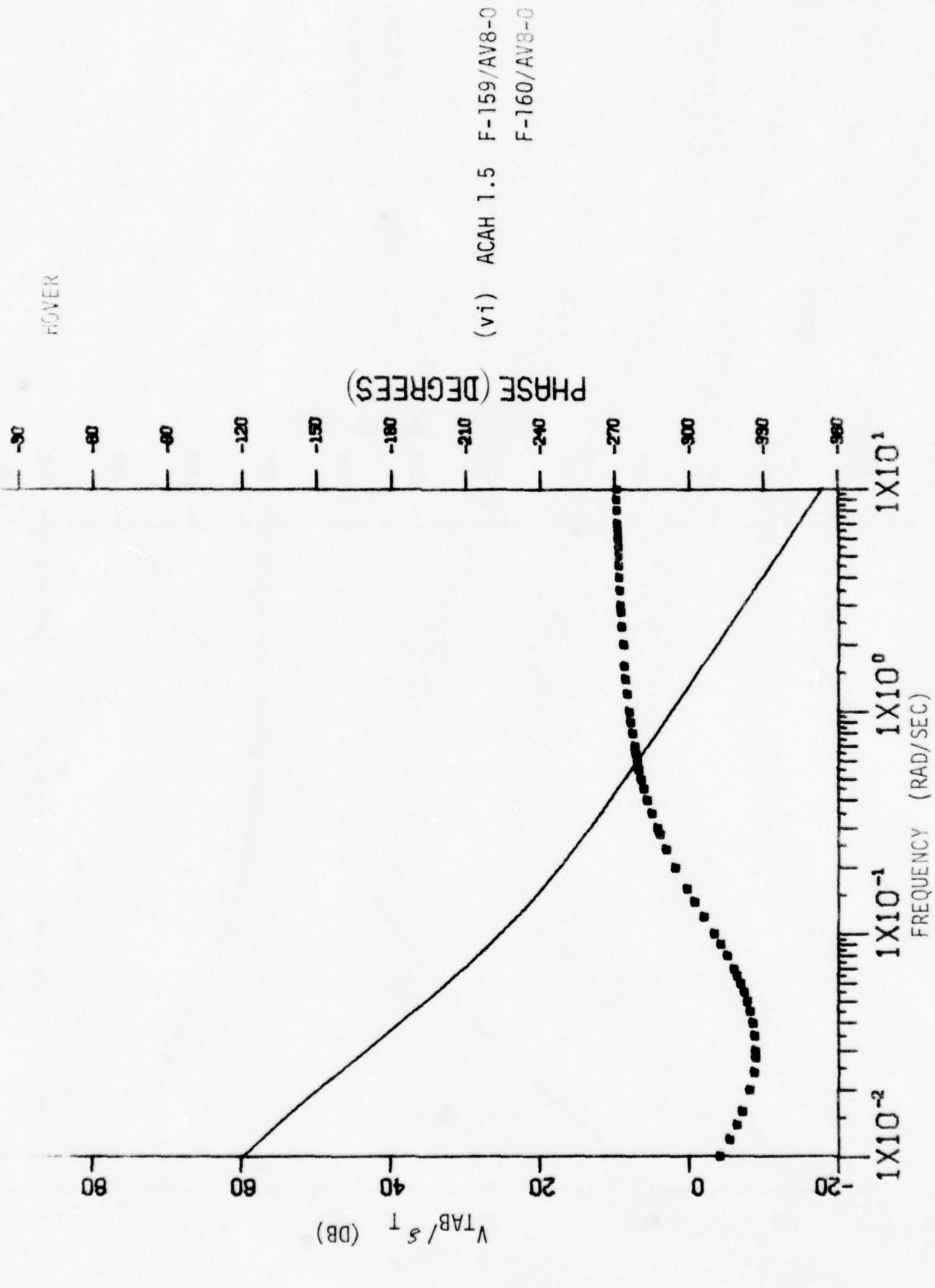


Figure I-6(a)(Cont) HOVER V_{TAB}/δ_T BODE PLOT

HOVER

(vii) ACAH 1.5 F-179/AV8-0
F-179/AV8-3

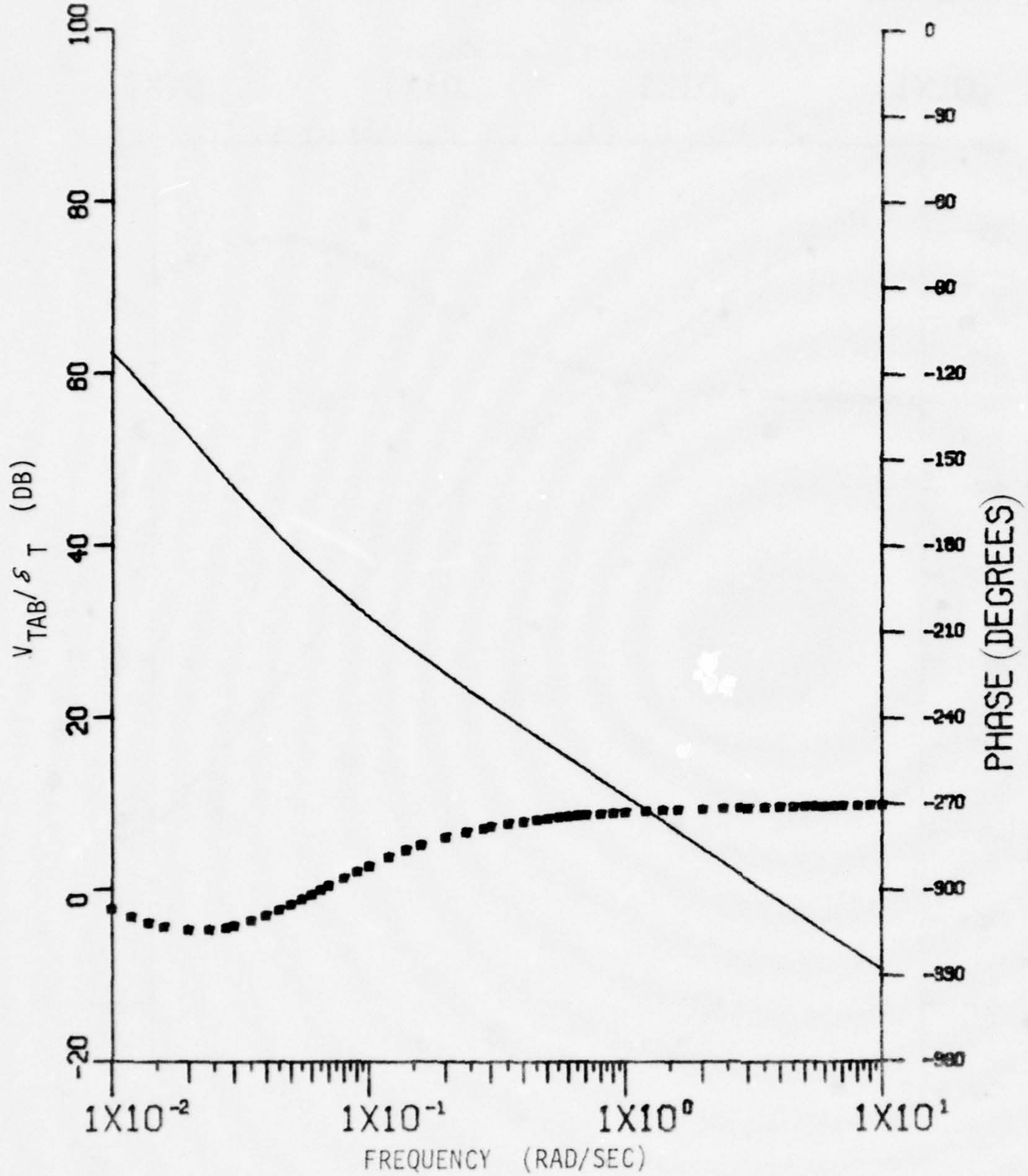


Figure I-6(a)(Cont) HOVER V_{TAB}/δ_T BODE PLOT

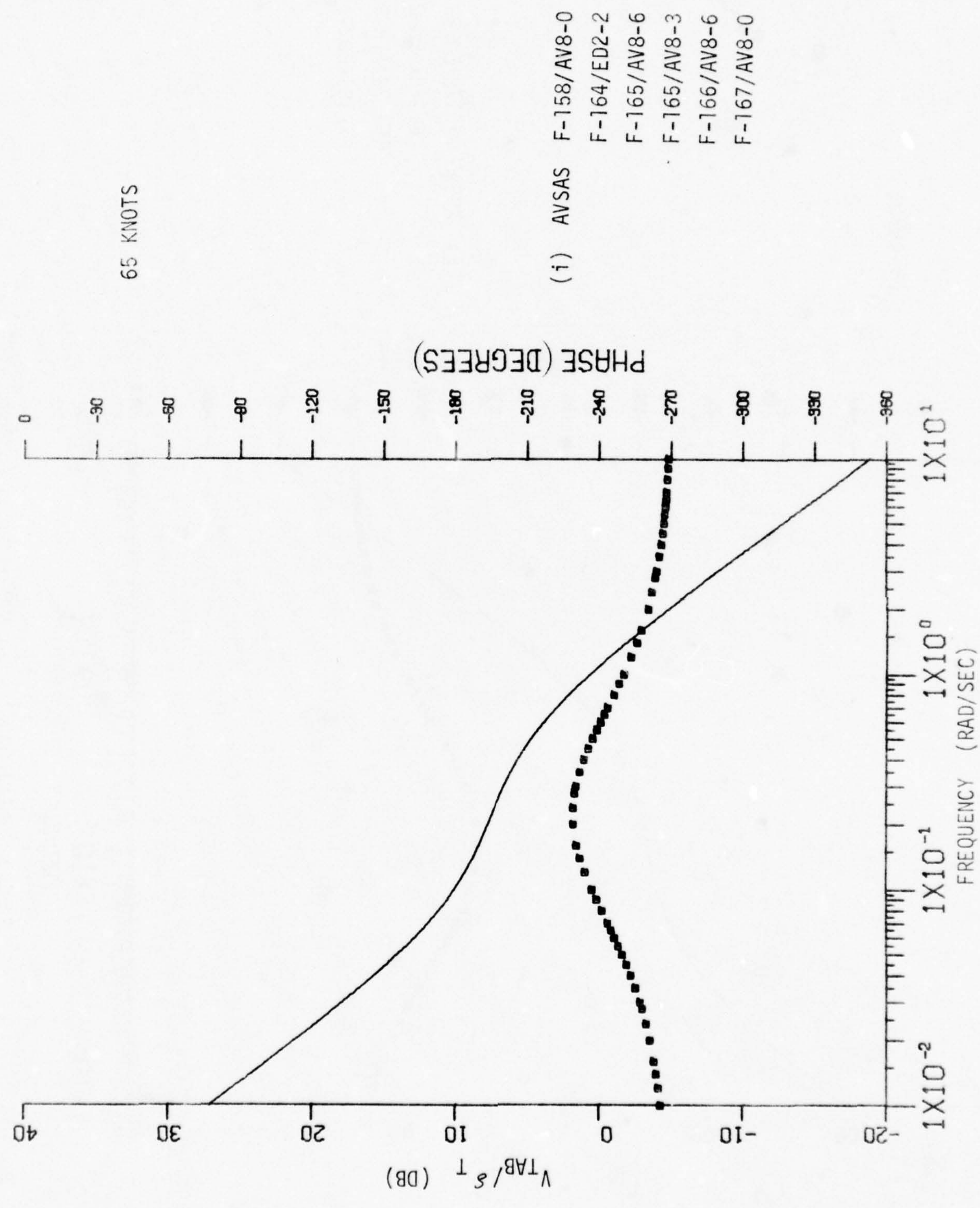


Figure I-6(b) 65 KNOTS V_{TAB}/δ_T BODE PLOT

65 KNOTS

(ii) AVSAS F-178/ED2-2
F-178/AV8-0
F-179/AV8-6
F-181/ED2-2

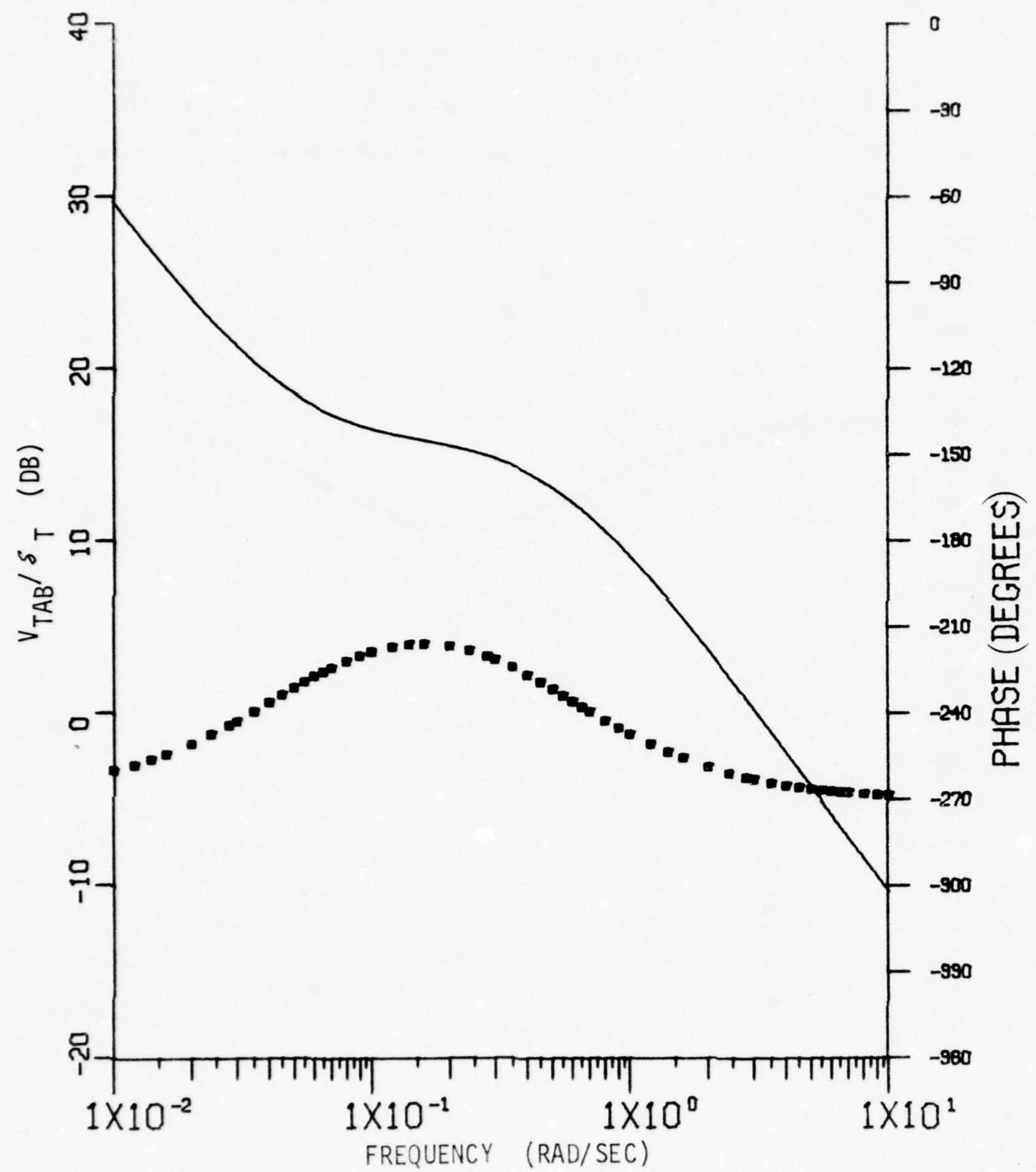


Figure I-6(b)(Cont) 65 KNOTS V_{TAB}/δ_T BODE PLOT

65 KNOTS

(iii) RCAH 2 F-169/AV8-3

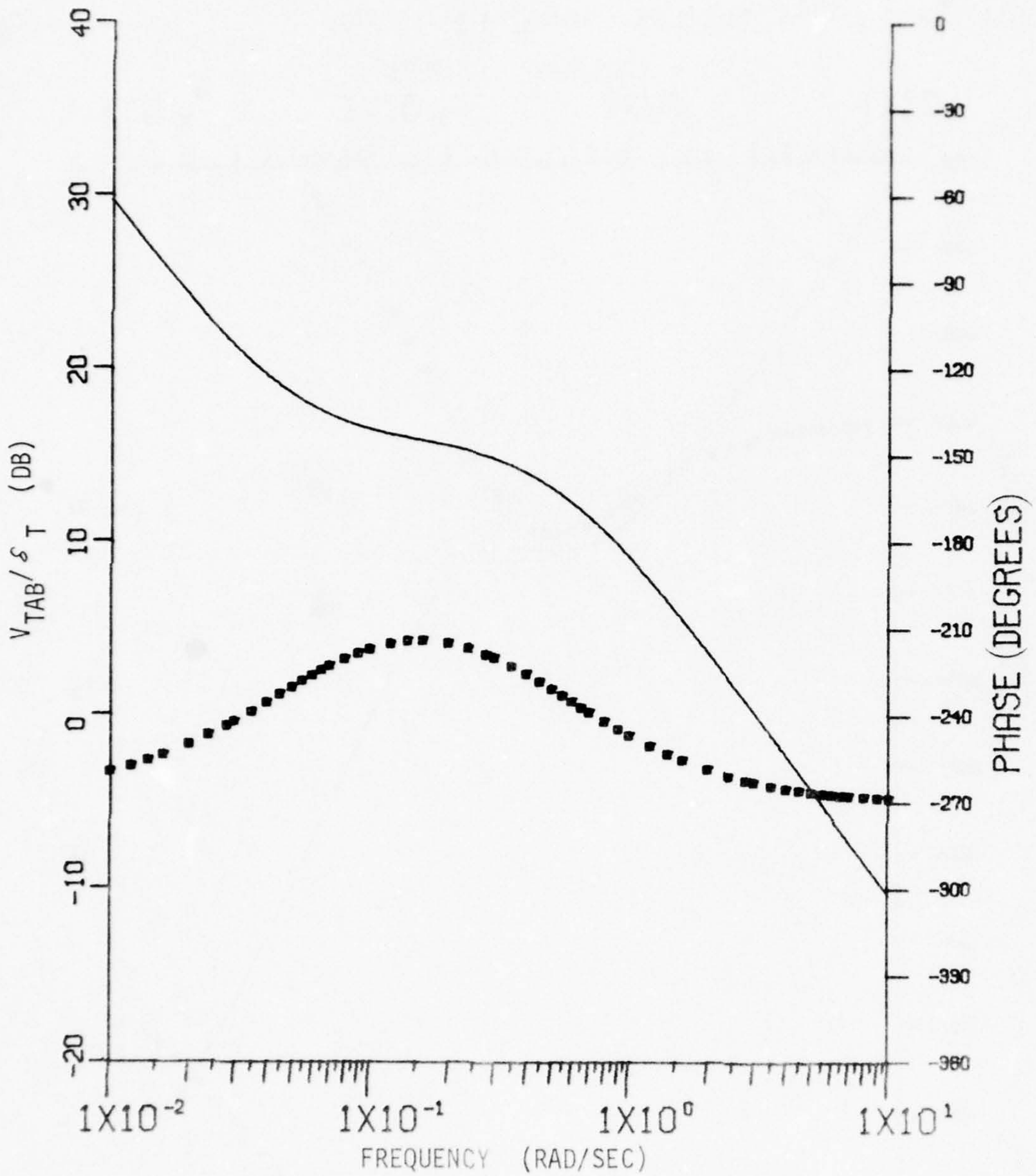


Figure I-6(b)(Cont) 65 KNOTS V_{TAB}/δ_T BODE PLOT

65 KNOTS

(iv) ACAH 1 F-164/AV8-6
F-165/ED2-2
F-166/AV8-6

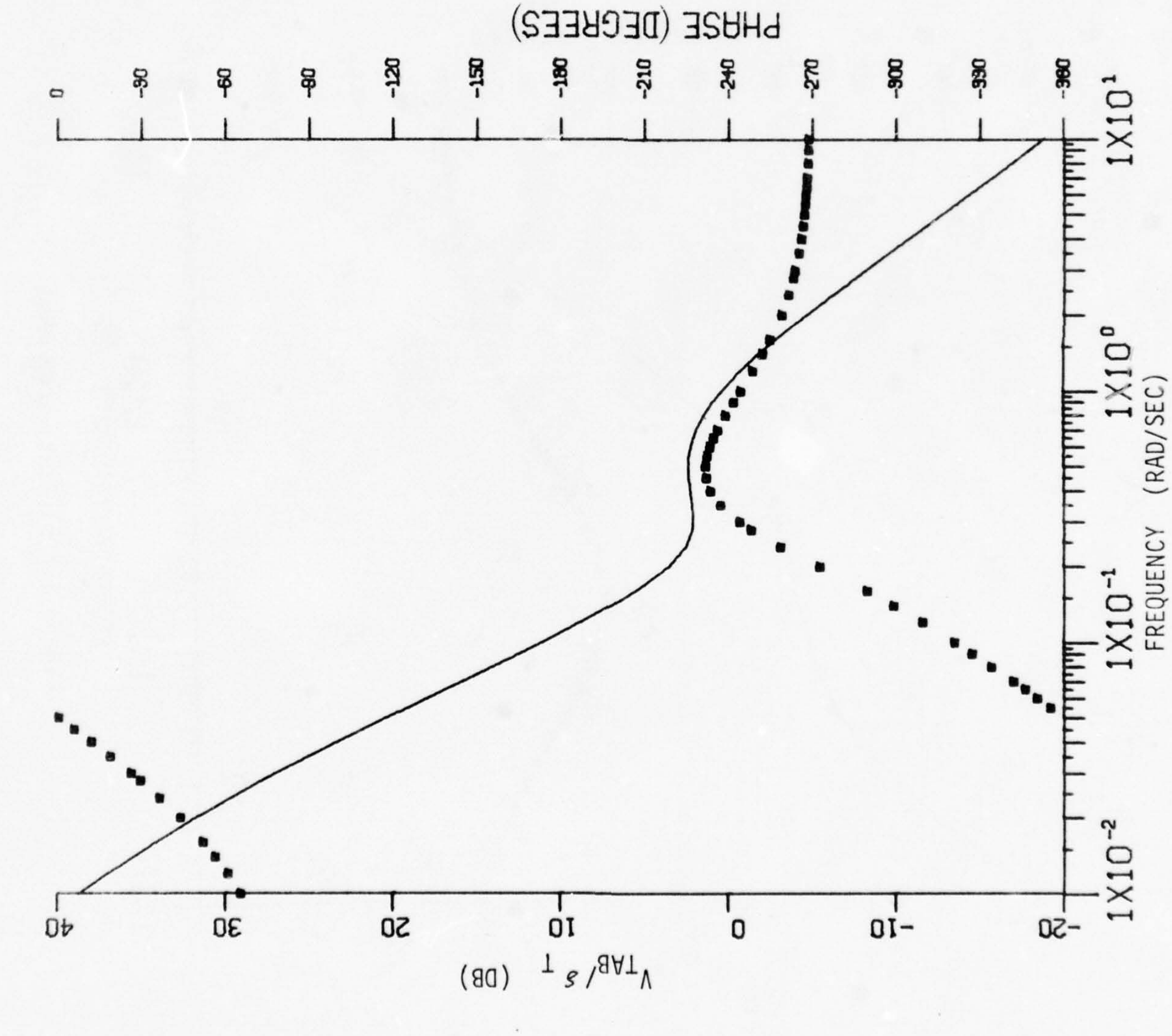


Figure I-6(b)(Cont) 65 KNOTS V_{TAB}/δ_T BODE PLOT

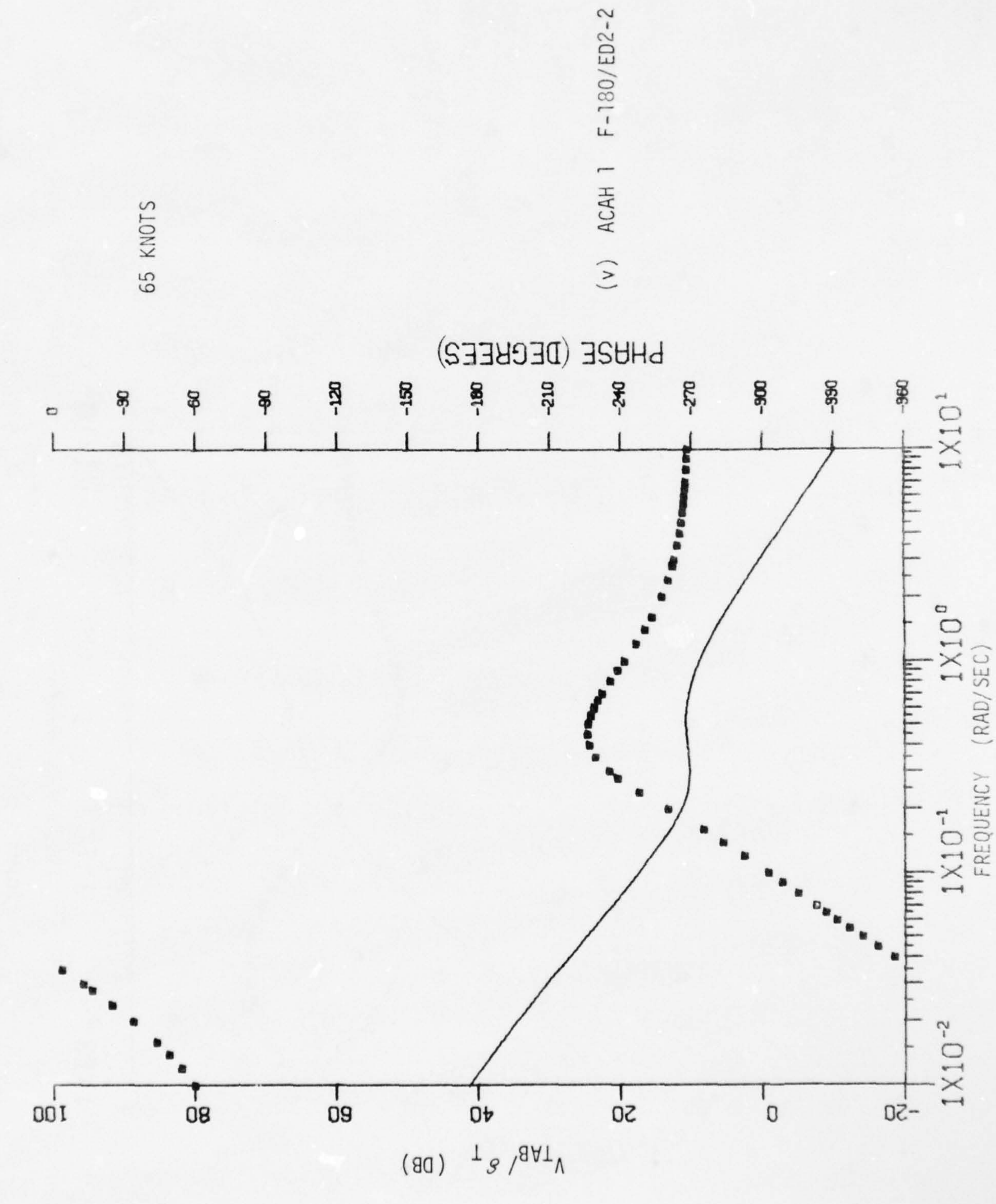


Figure I-6(b)(Cont) 65 KNOTS V_{TAB}/δ_T BODE PLOT

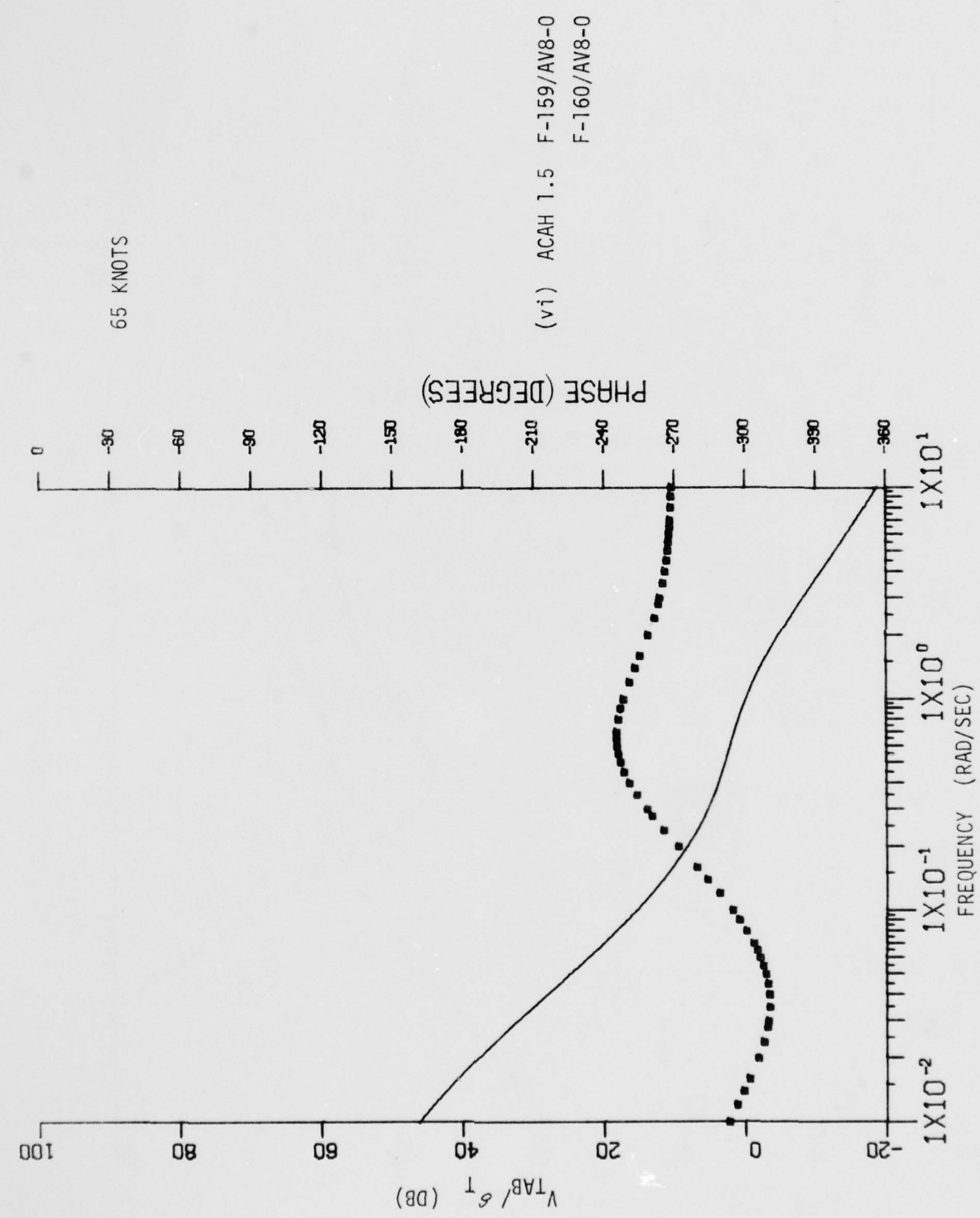


Figure I-6(b)(Cont) 65 KNOTS V_{TAB}/δ_T BODE PLOT

65 KNOTS

(vii) ACAH 1.5 F-179/AV8-0
F-179/AV8-3

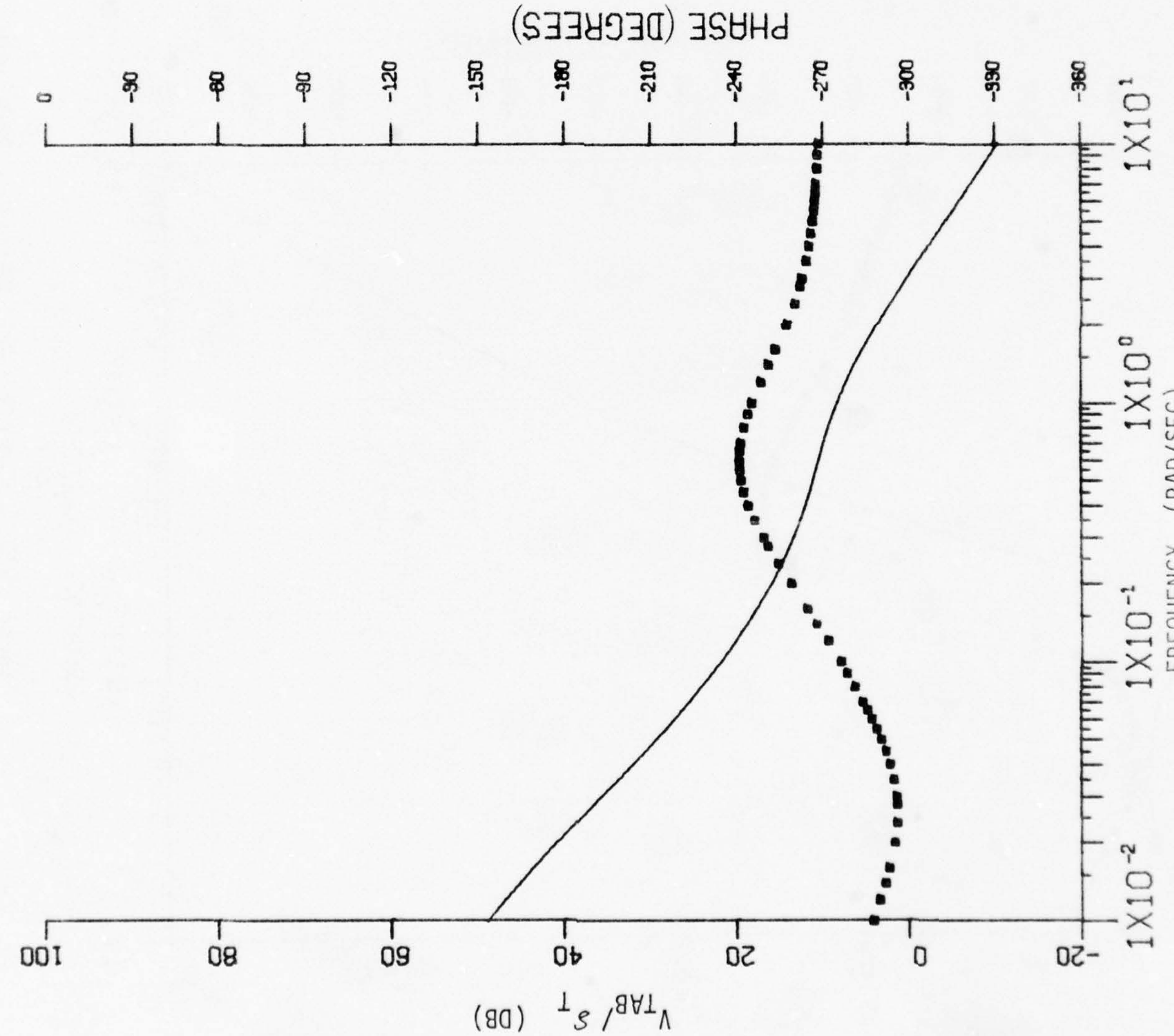


Figure I-6(b)(Cont) 65 KNOTS V_{TAB}/δ_T BODE PLOT

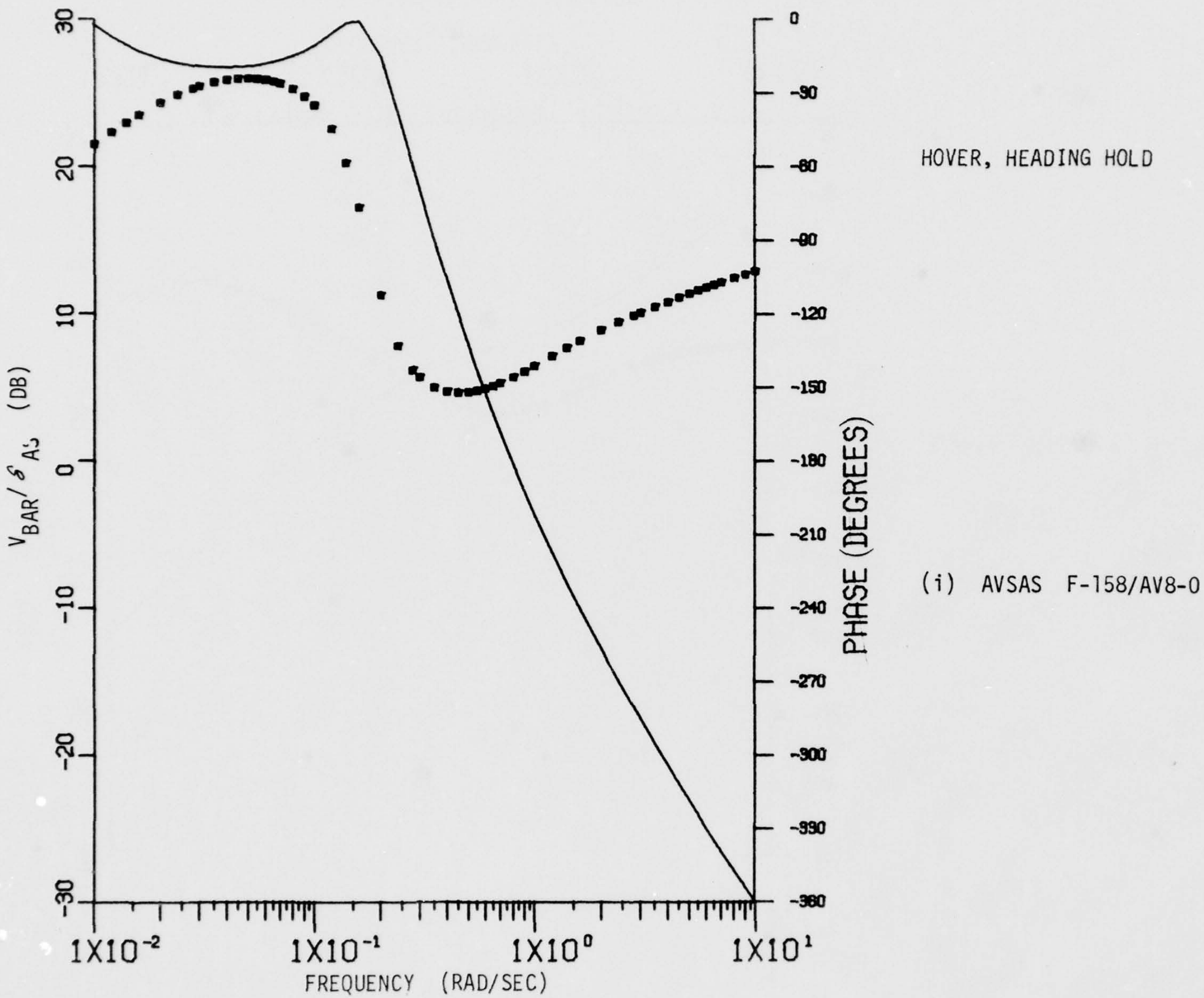


Figure I-7(a) HOVER (HH) V_{BAR}/δ_{AS} BODE PLOT

HOVER, HEADING HOLD

(ii) AVSAS F-164/ED2-2

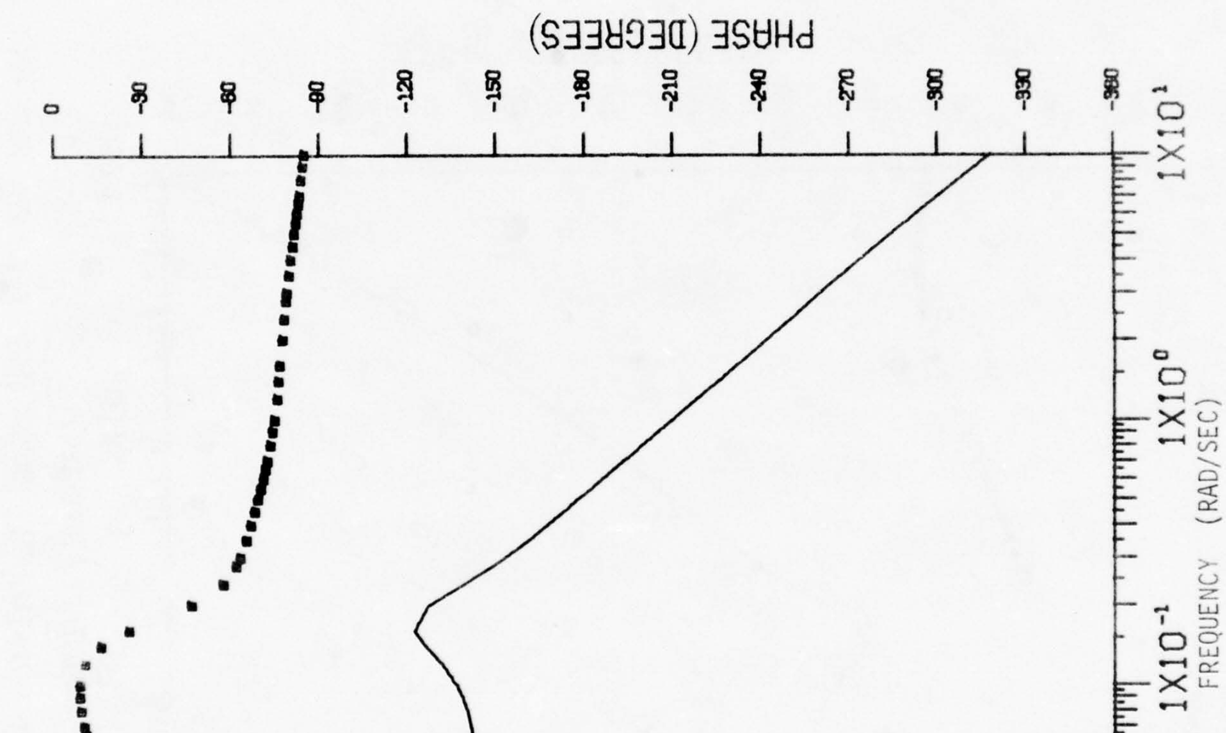


Figure I-7(a)(Cont) HOVER (HH) V_{BAR}/δ_{AS} BODE PLOT

HOVER, HEADING HOLD

(iii) AVSAS F-165/AV8-6
F-165/AV8-3

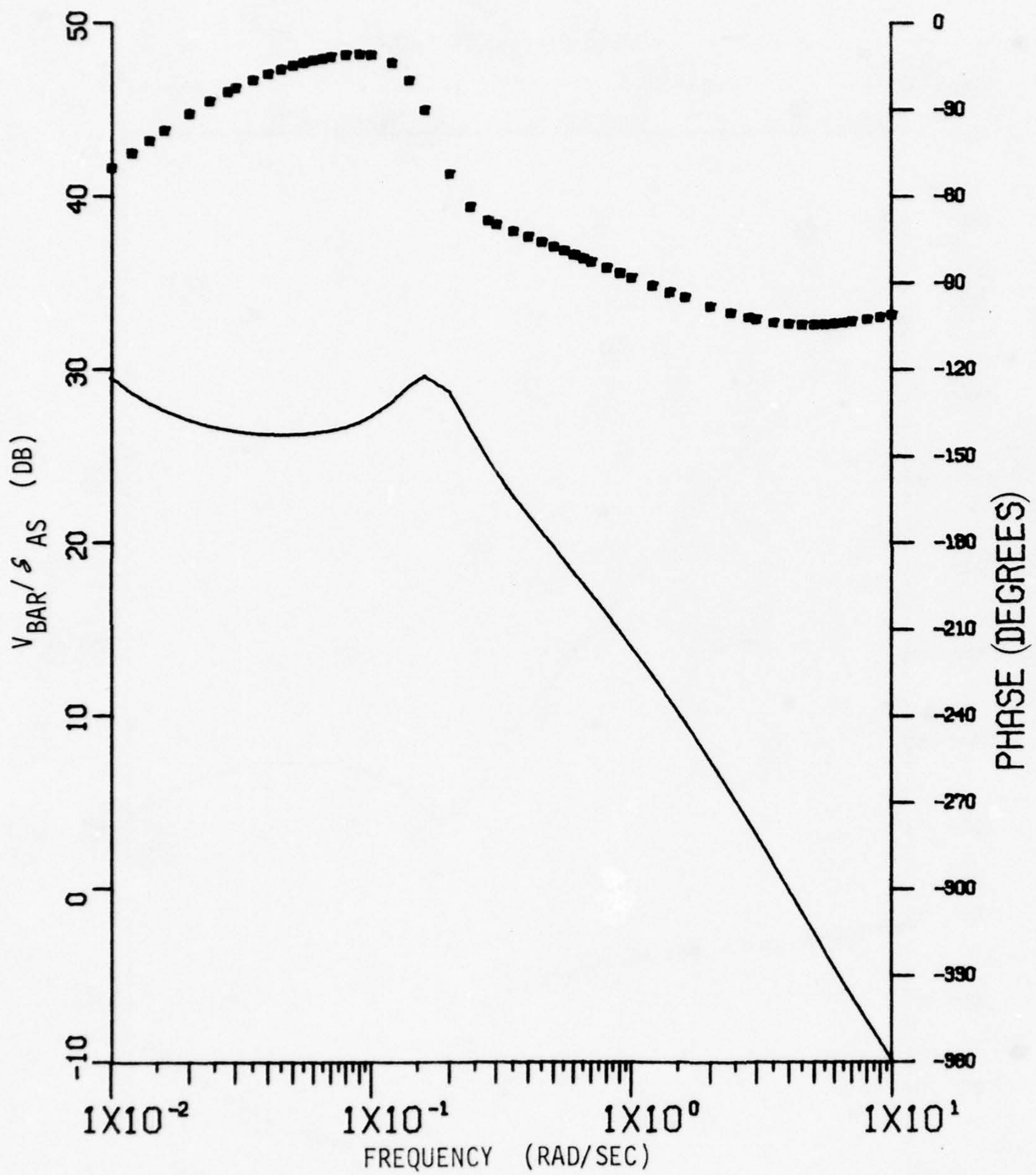


Figure I-7(a)(Cont) HOVER (HH) V_{BAR}/δ_{AS} BODE PLOT

HOVER, HEADING HOLD

(iv) AVSAS F-166/AV8-6
F-167/AV8-0
F-178/ED2-2
F-178/AV8-0
F-179/AV8-6
F-181/ED2-2

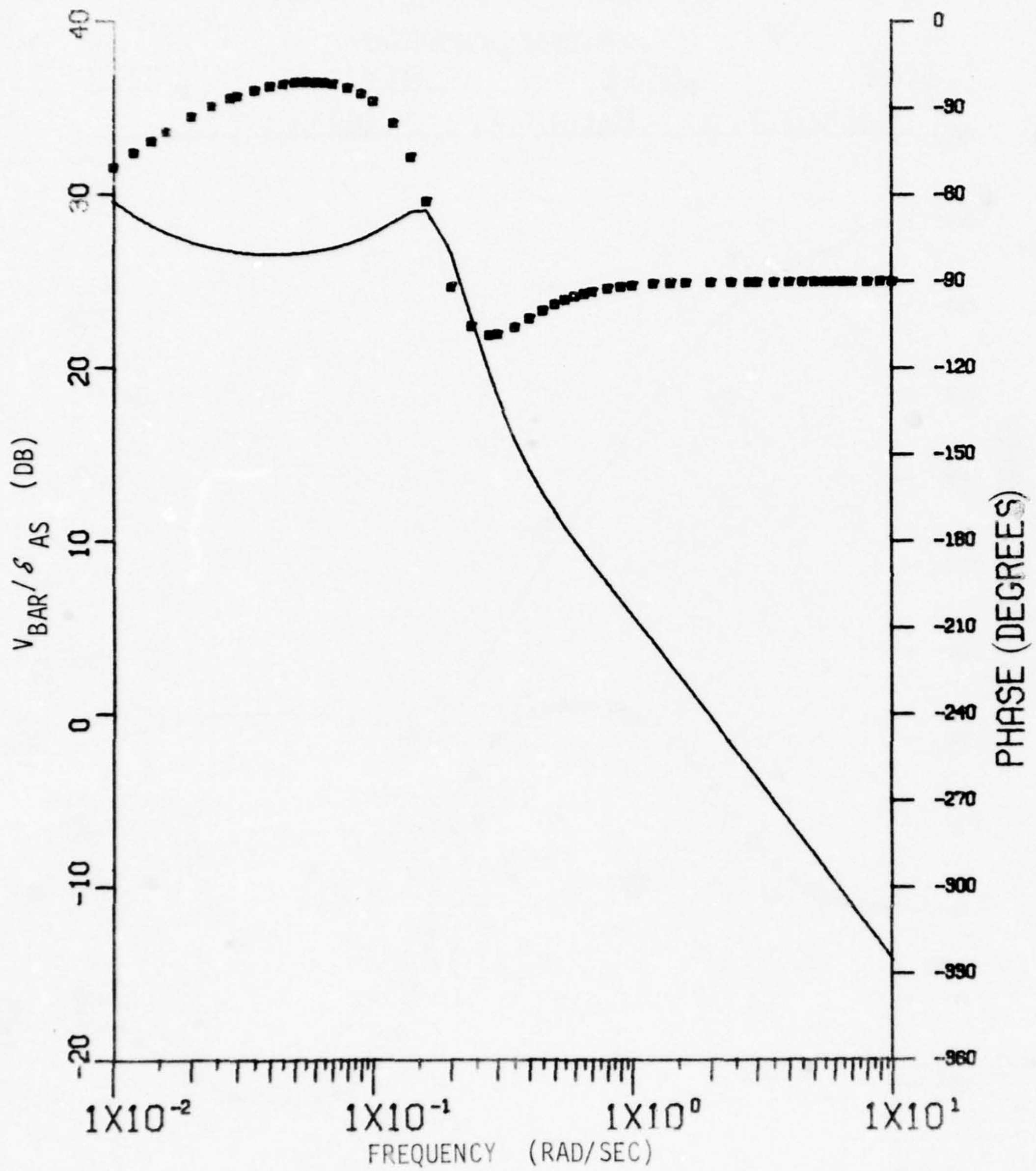


Figure I-7(a)(Cont) HOVER (HH) V_{BAR}/δ_{AS} BODE PLOT

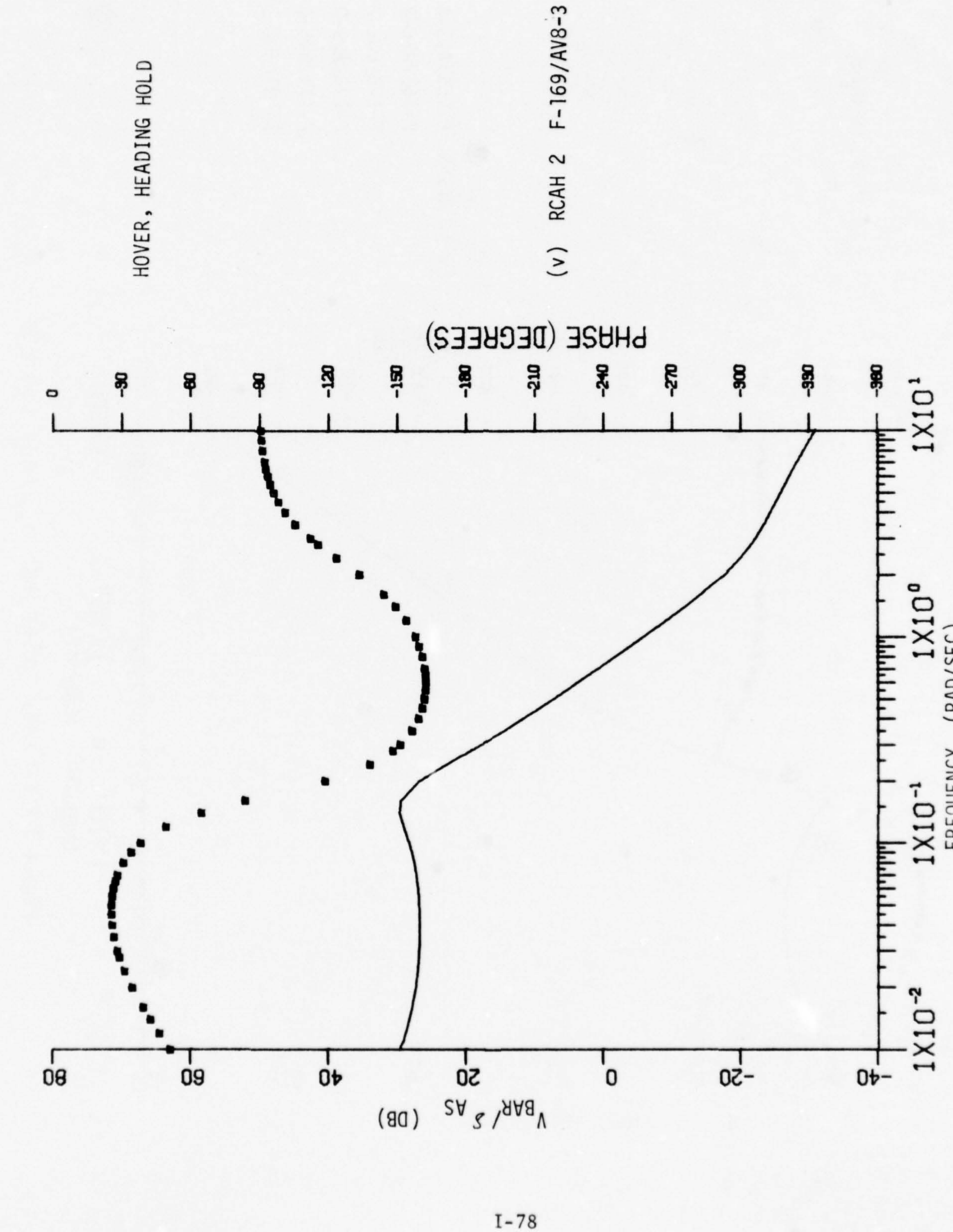


Figure I-7(a)(Cont) HOVER (HH) V_{BAR}/δ_{AS} BODE PLOT

HOVER, HEADING HOLD

(vi) ACAH 1 F-164/AV8-6

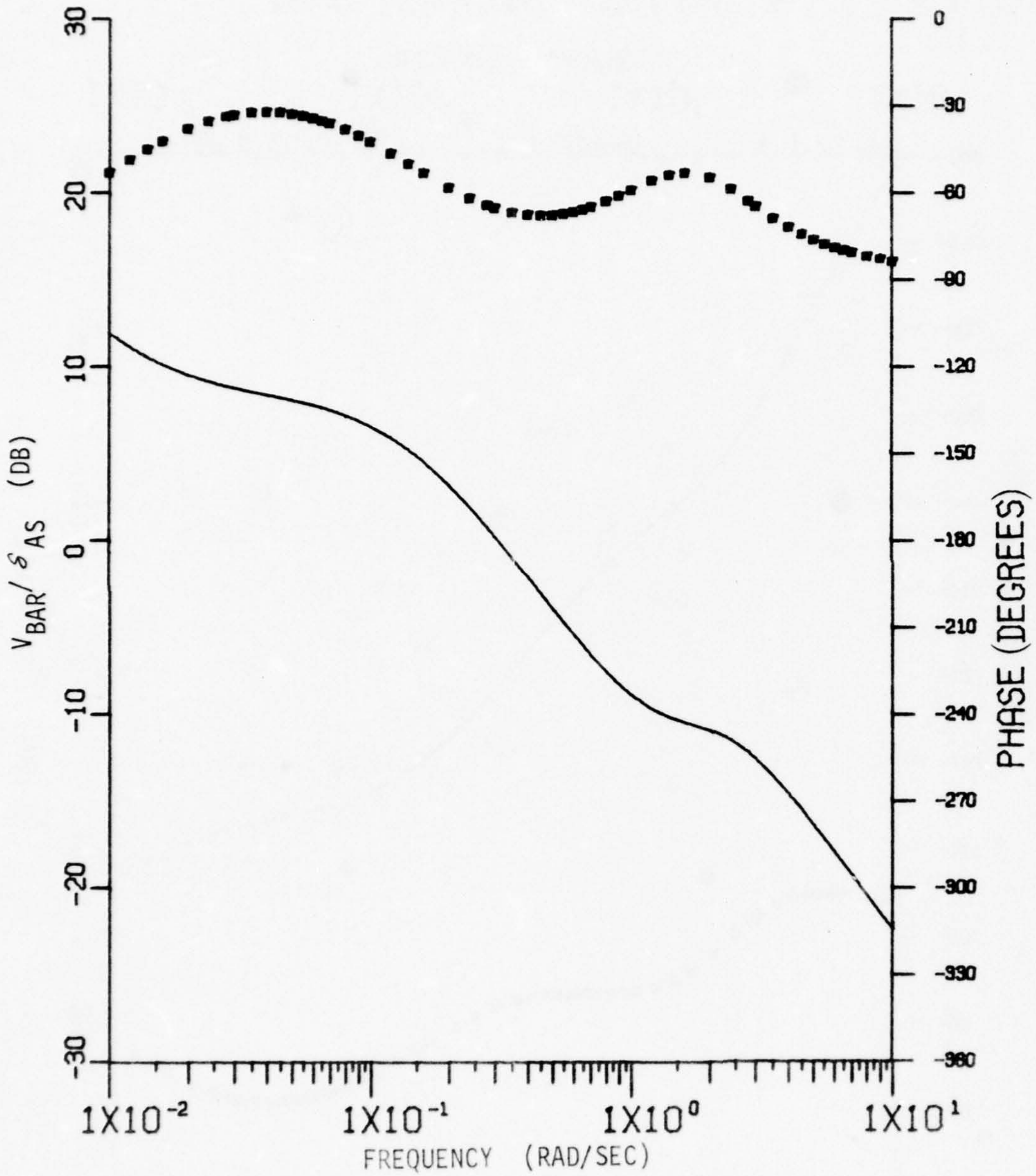


Figure I-7(a)(Cont) HOVER (HH) V_{BAR}/δ_{AS} BODE PLOT

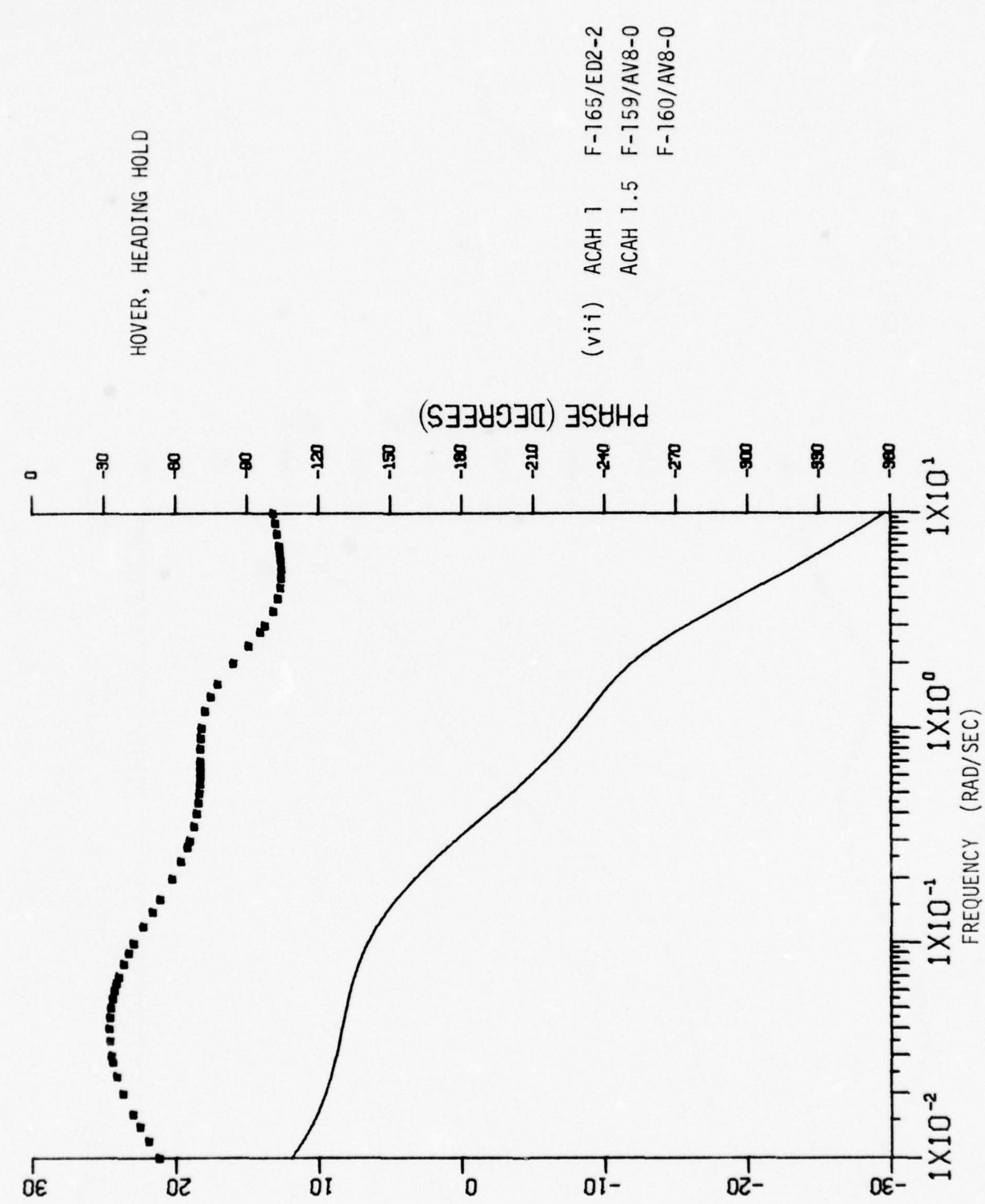


Figure I-7(a)(Cont) HOVER (HH) V_{BAR}/δ_{AS} BODE PLOT

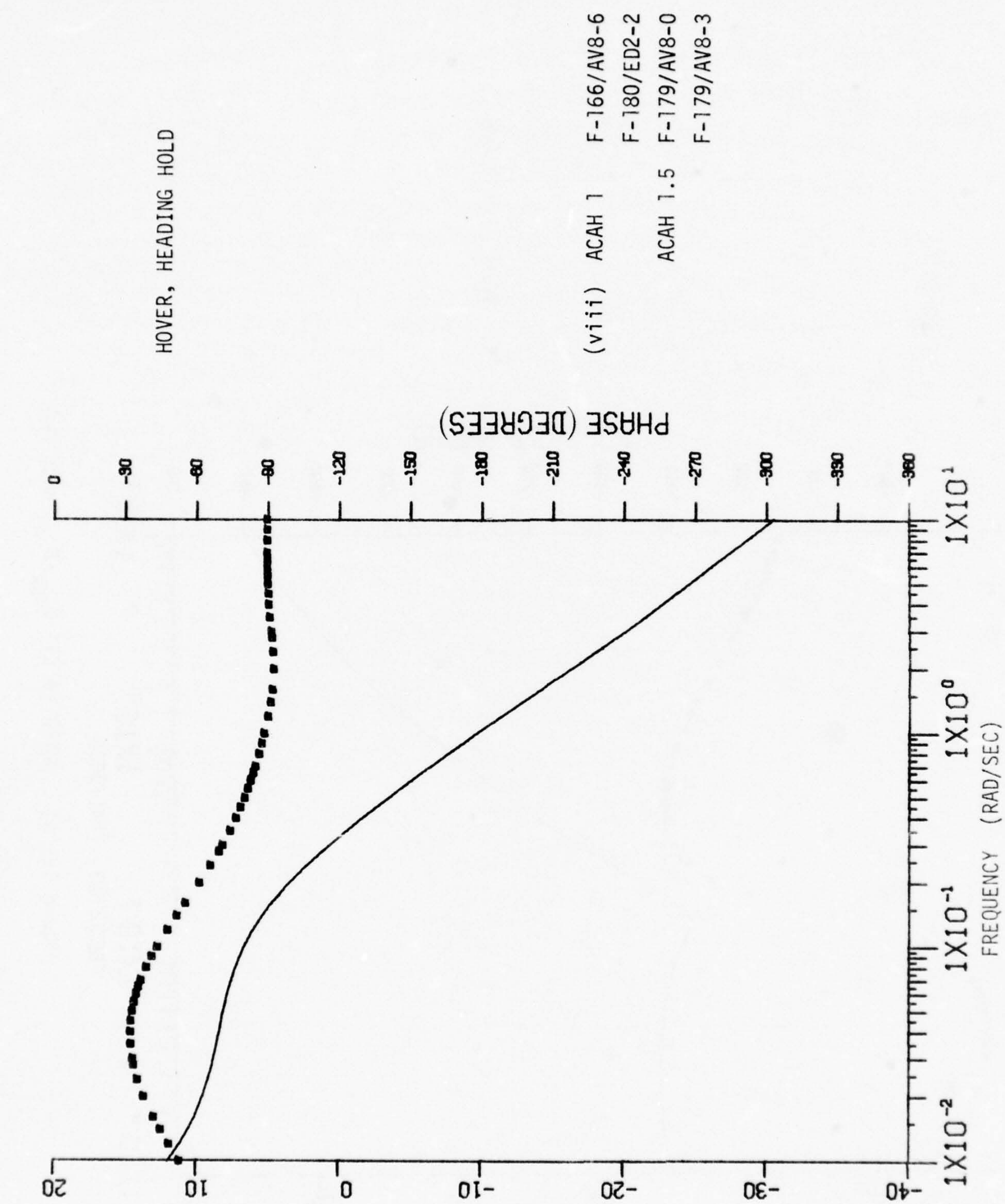


Figure I-7(a)(Cont) HOVER (HH) V_{BAR}/δ_{AS} BODE PLOT

HOVER (ATC)

(i) AVSAS F-158/AV8-0

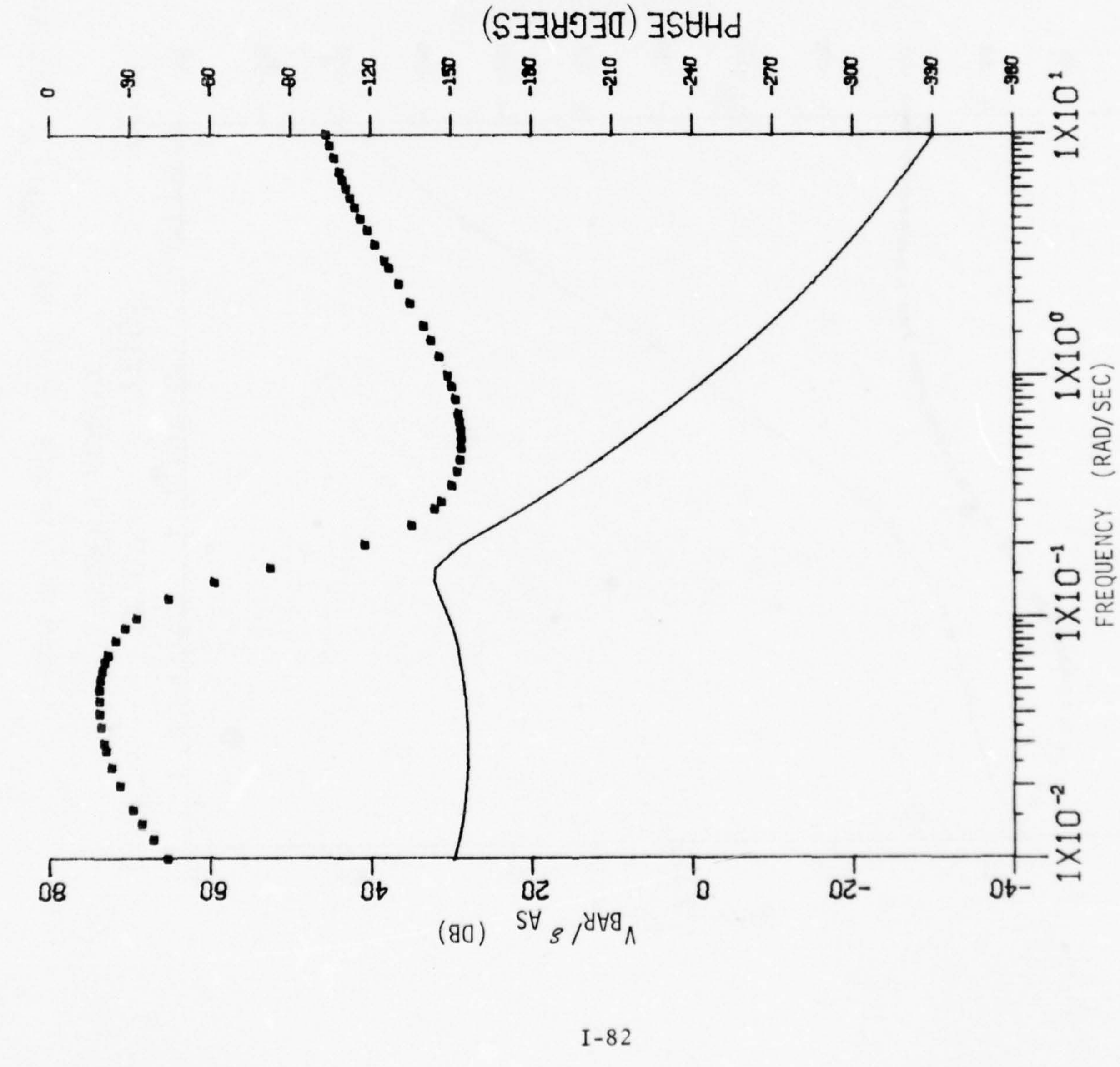


Figure I-7(b) HOVER (ATC) V_{BAR}/δ_{AS} BODE PLOT

HOVER (ATC)

(ii) AVSAS F-164/ED2-2

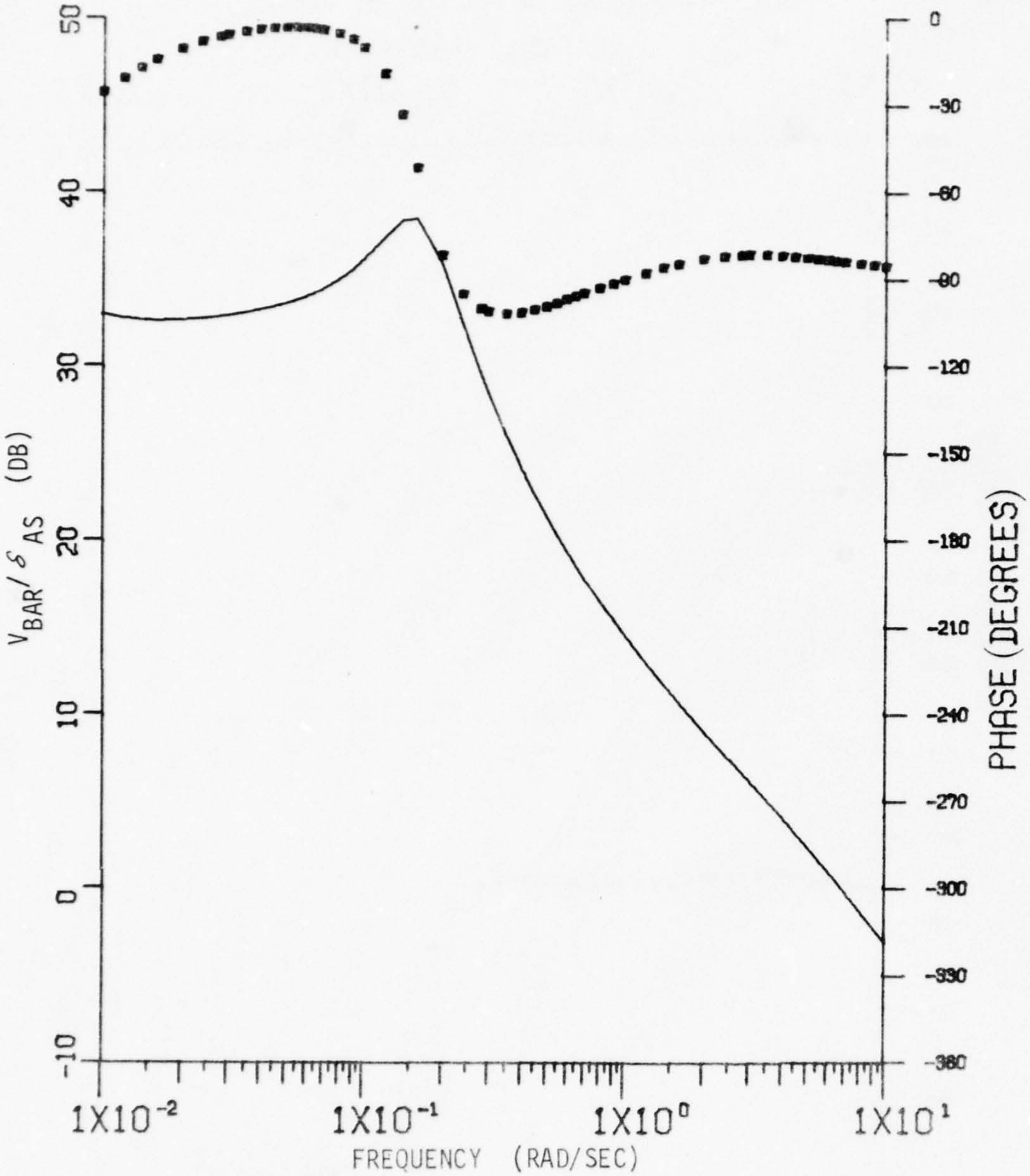
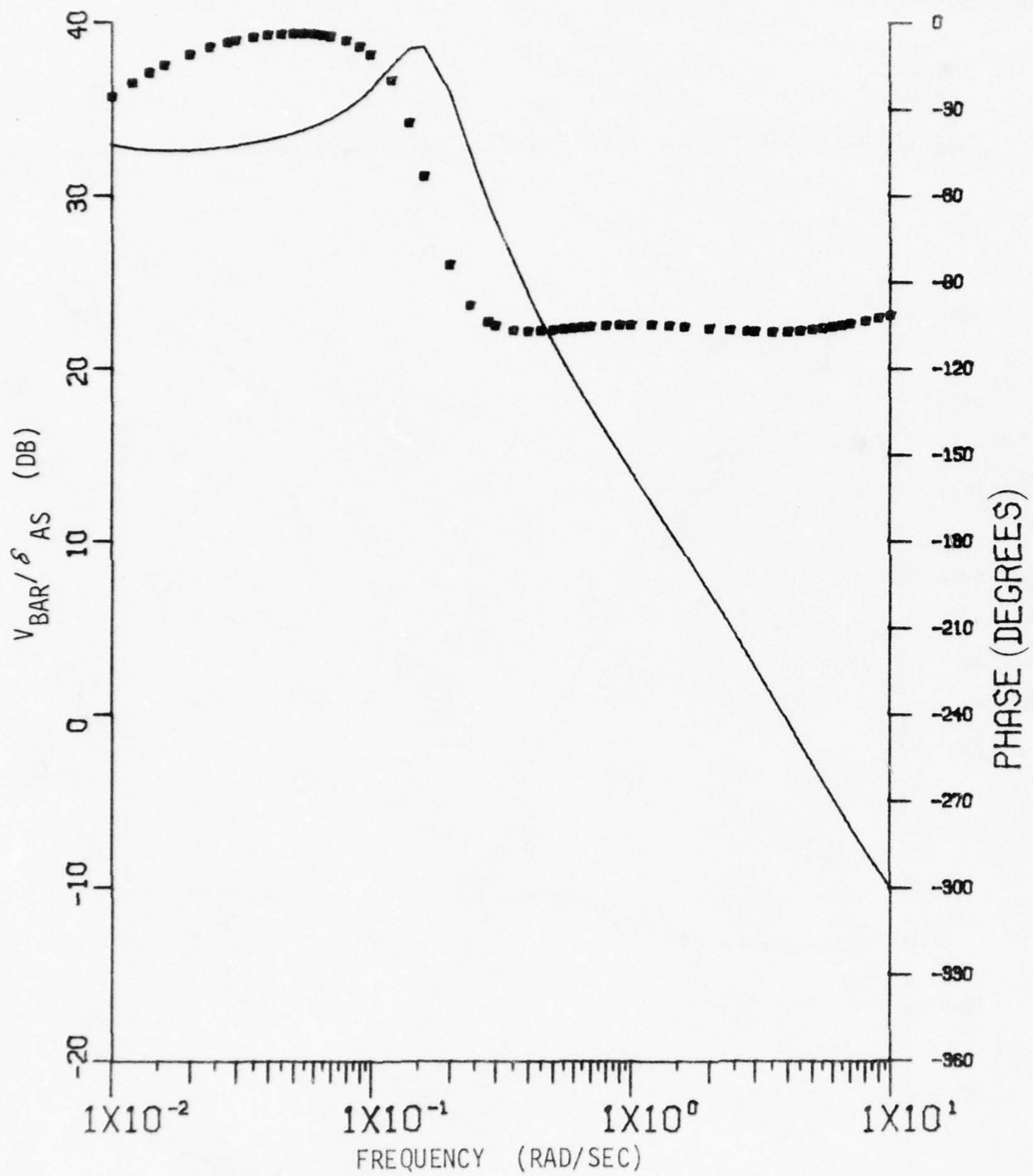


Figure I-7(b)(Cont) HOVER (ATC) V_{BAR}/δ_{AS} BODE PLOT



HOVER (ATC)

(iii) AVSAS F-165/AV8-6
F-165/AV8-3

Figure I-7(b)(Cont) HOVER (ATC) V_{BAR}/δ_{AS} BODE PLOT

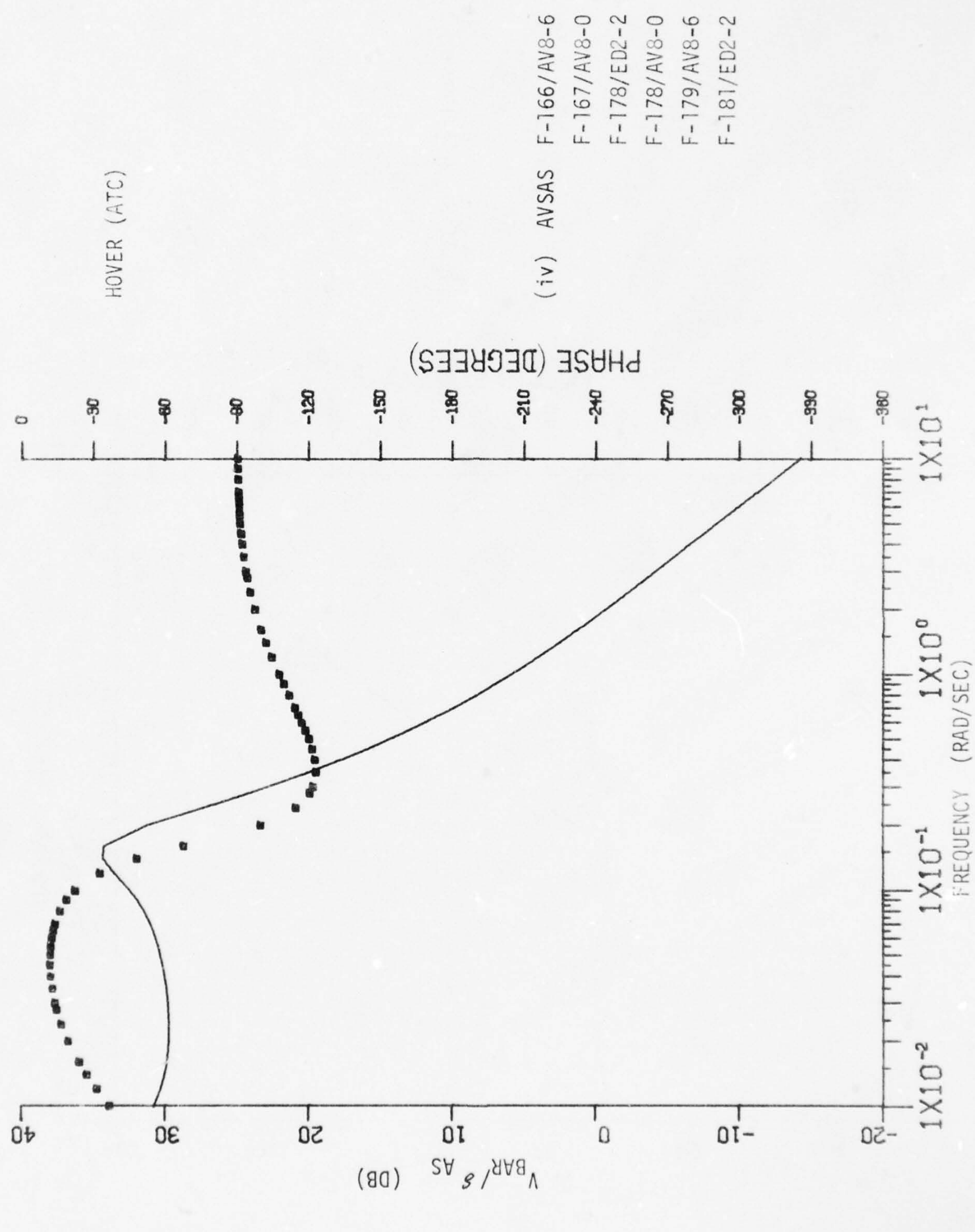


Figure I-7(b)(Cont) HOVER (ATC) V_{BAR}/δ_{AS} BODE PLOT

HOVER (ATC)

(v) RCAH 2 F-169/AV8-3

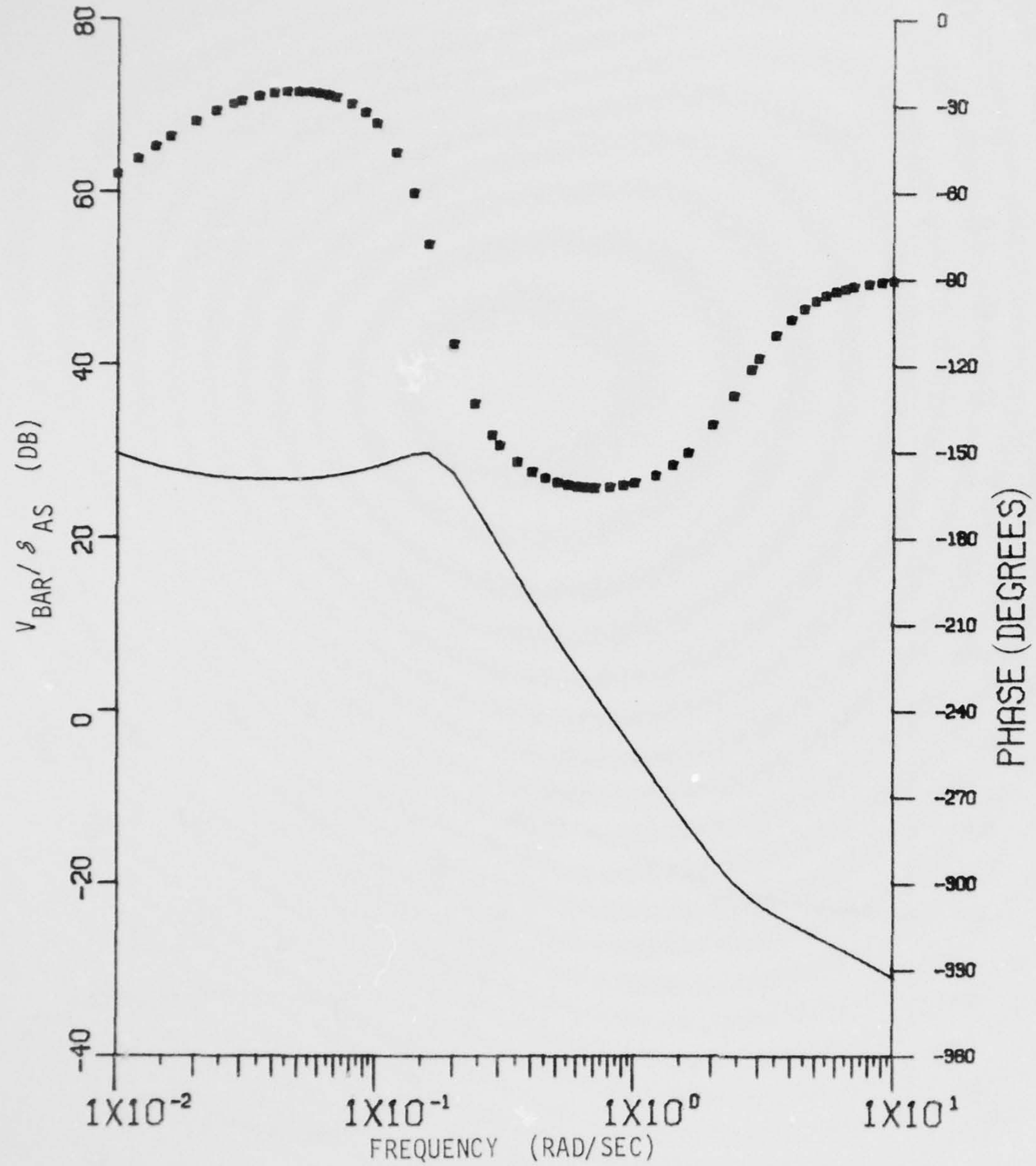


Figure I-7(b)(Cont) HOVER (ATC) V_{BAR}/δ_{AS} BODE PLOT

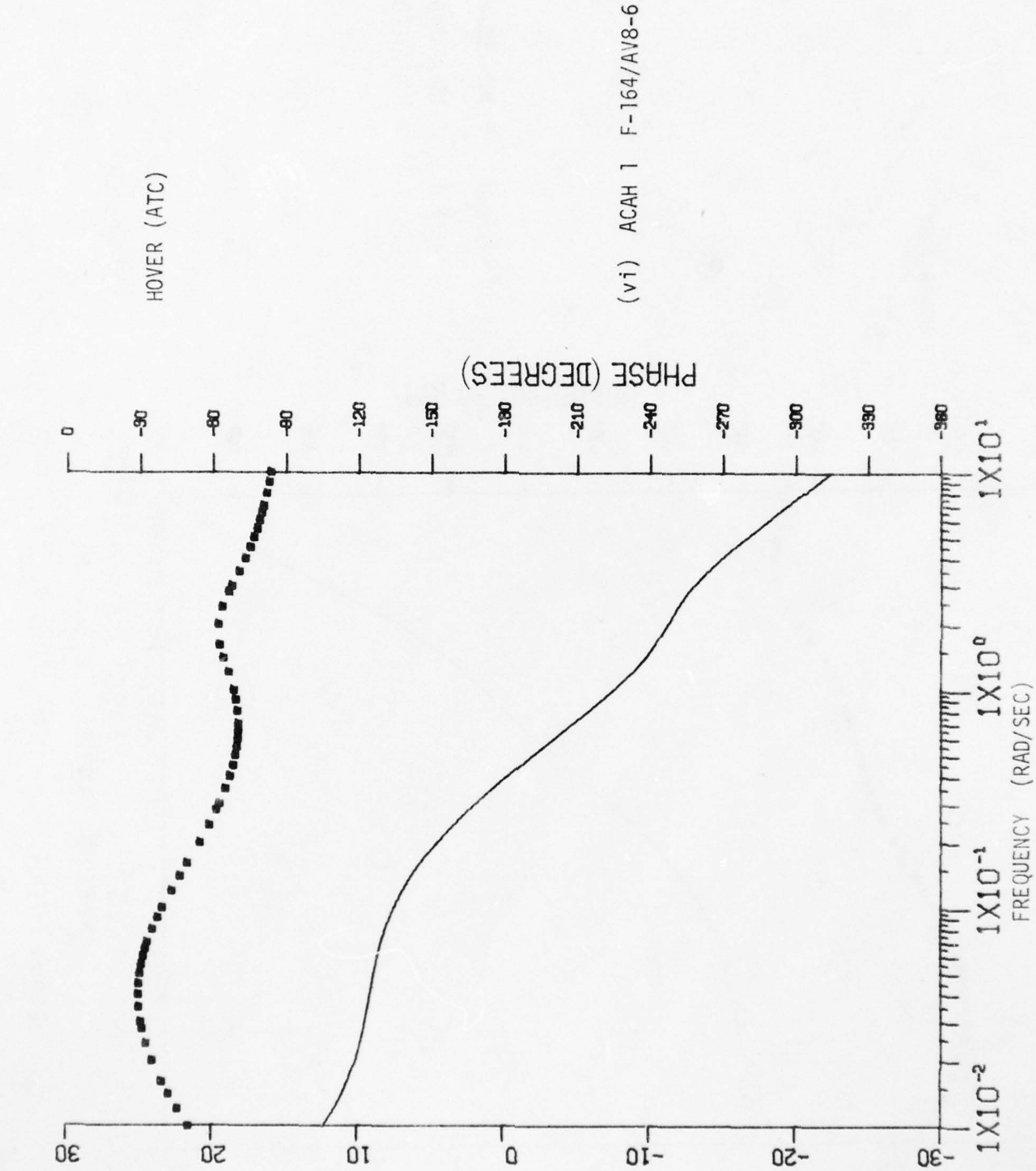
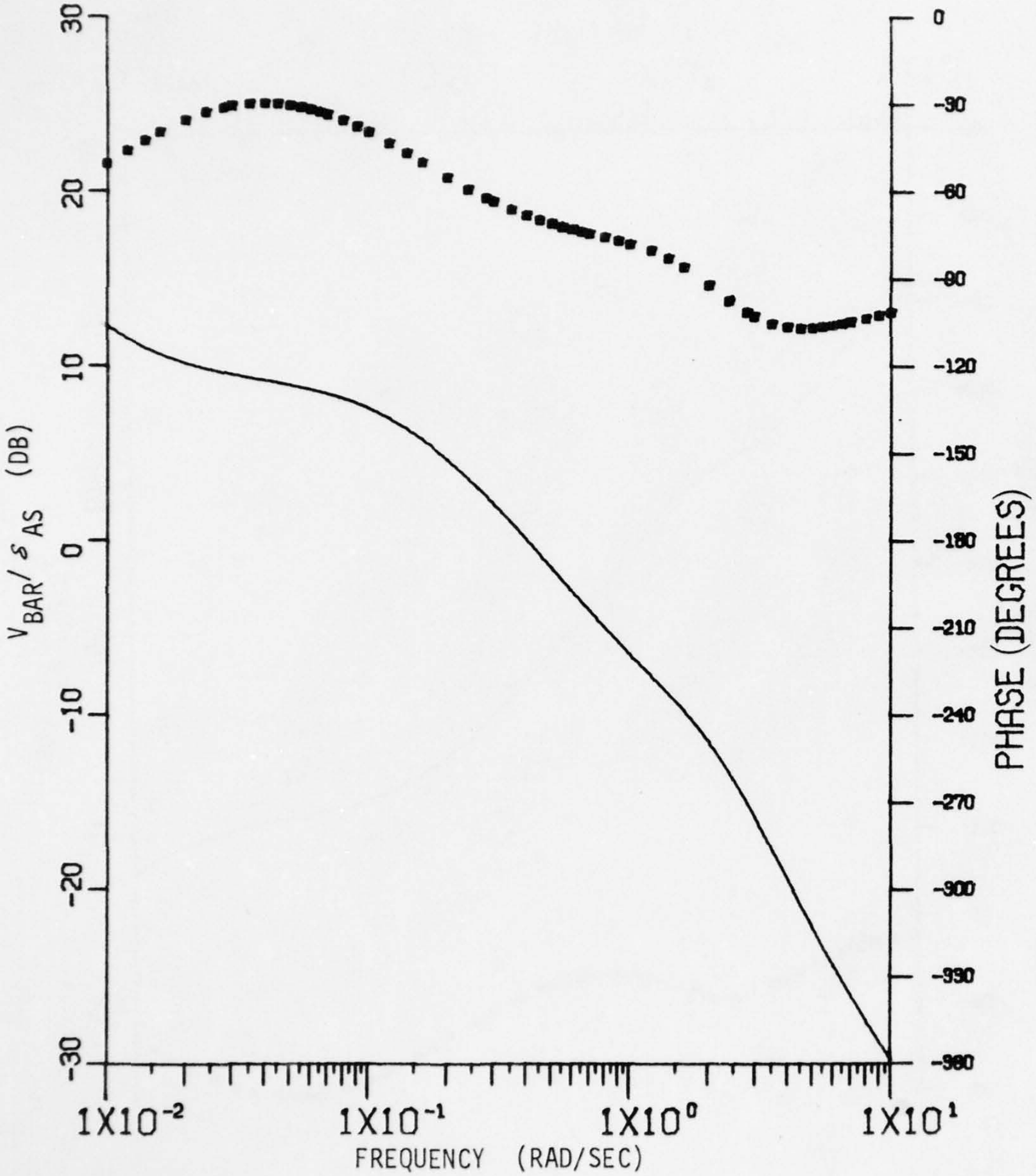


Figure I-7(b)(Cont) HOVER (ATC) V_{BAR}/δ_{AS} BODE PLOT



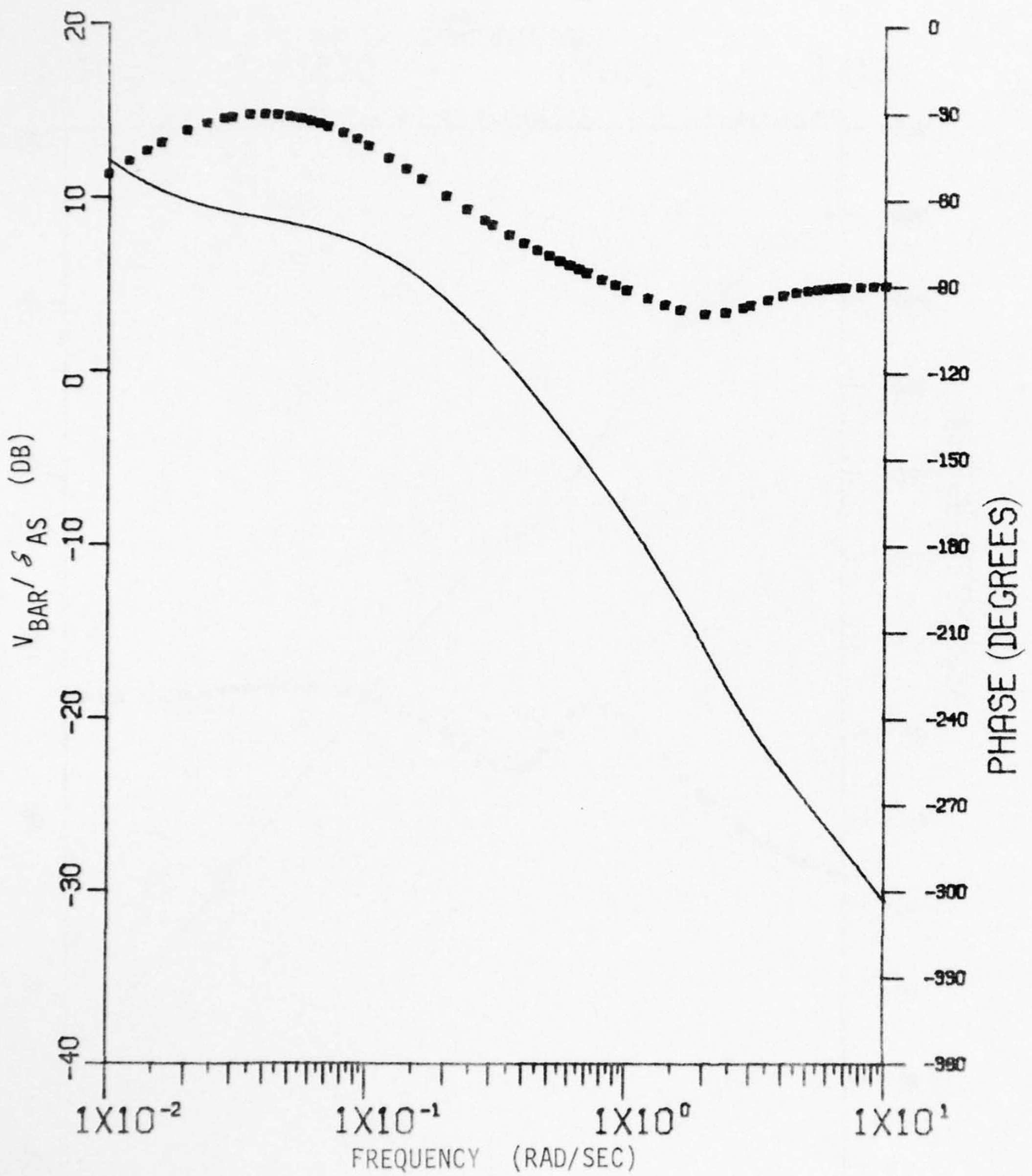
HOVER (ATC)

(vii) ACAH 1 F-165/ED2-2

ACAH 1.5 F-159/AV8-0

F-160/AV8-0

Figure I-7(b)(Cont) HOVER (ATC) V_{BAR}/δ_{AS} BODE PLOT



HOVER (ATC)

(viii) ACAH 1 F-166/AV8-6
F-180/ED2-2
ACAH 1.5 F-179/AV8-0
F-179/AV8-3

Figure I-7(b)(Cont) HOVER (ATC) V_{BAR}/δ_{AS} BODE PLOT

65 KNOTS (ATC)

(i) AVSAS F-158/AV8-0

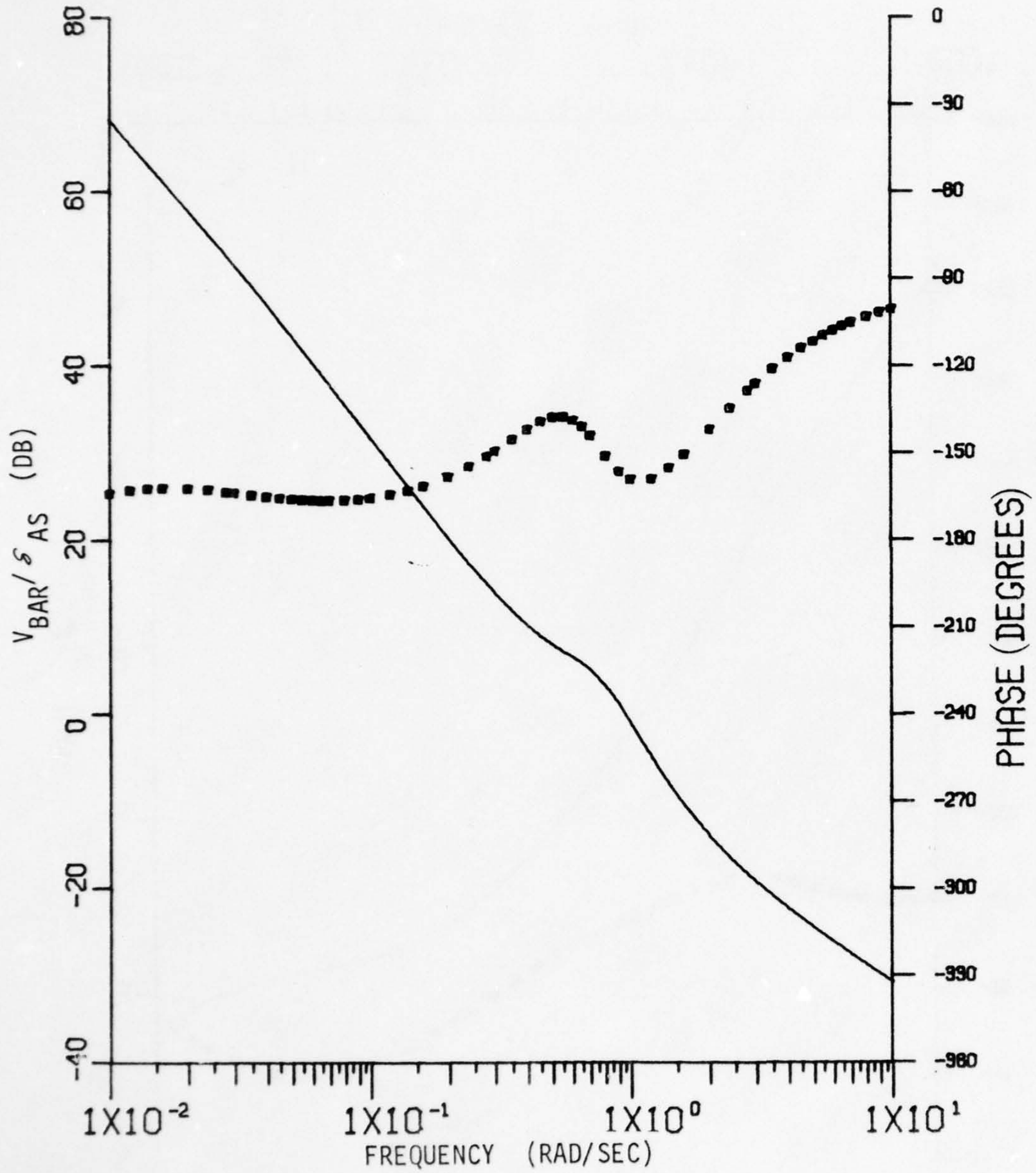


Figure I-7(c) 65 KNOTS (ATC) V_{BAR}/δ_{AS} BODE PLOT

65 KNOTS (ATC)

(ii) AVSAS F-164/ED2-2

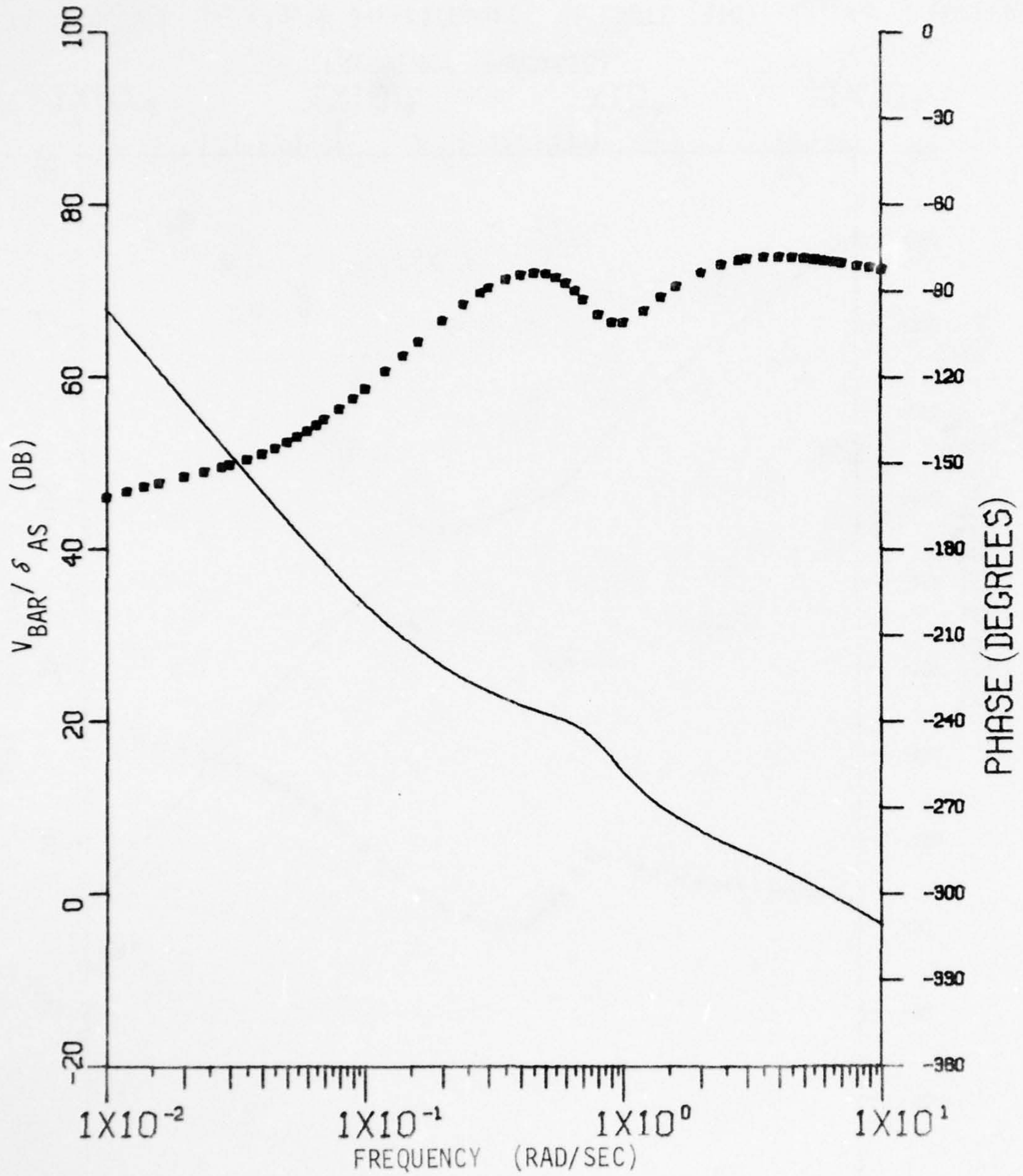


Figure I-7(c)(Cont) 65 KNOTS (ATC) V_{BAR}/δ_{AS} BODE PLOT

65 KNOTS (ATC)

(iii) AVSAS F-165/AV8-6
F-165/AV8-3

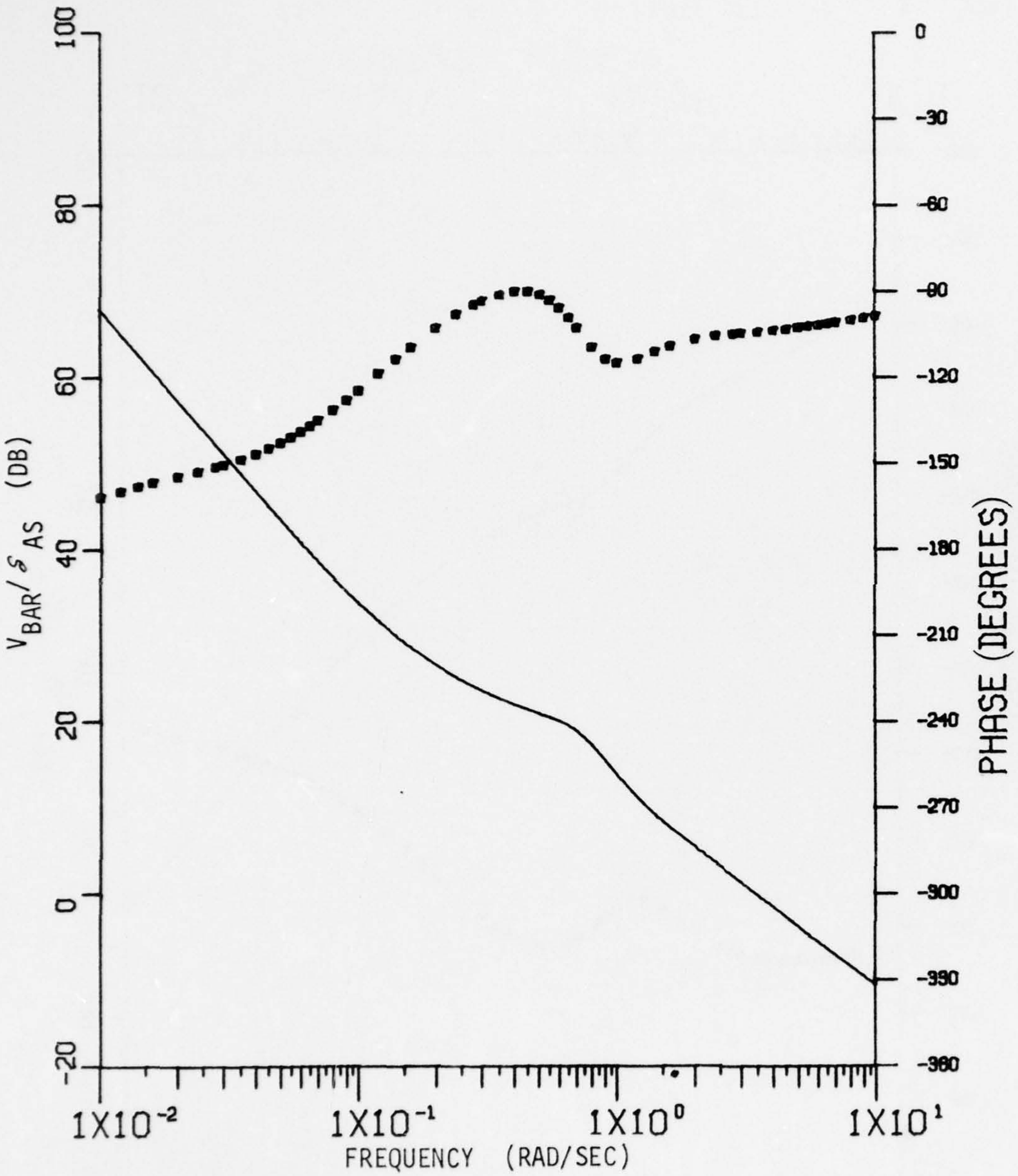


Figure I-7(c)(Cont) 65 KNOTS (ATC) V_{BAR}/δ_{AS} BODE PLOT

65 KNOTS (ATC)

(iv) AVSAS F-166/AV8-6
F-167/AV8-0
F-178/ED2-2
F-178/AV8-0
F-179/AV8-6
F-181/ED2-2

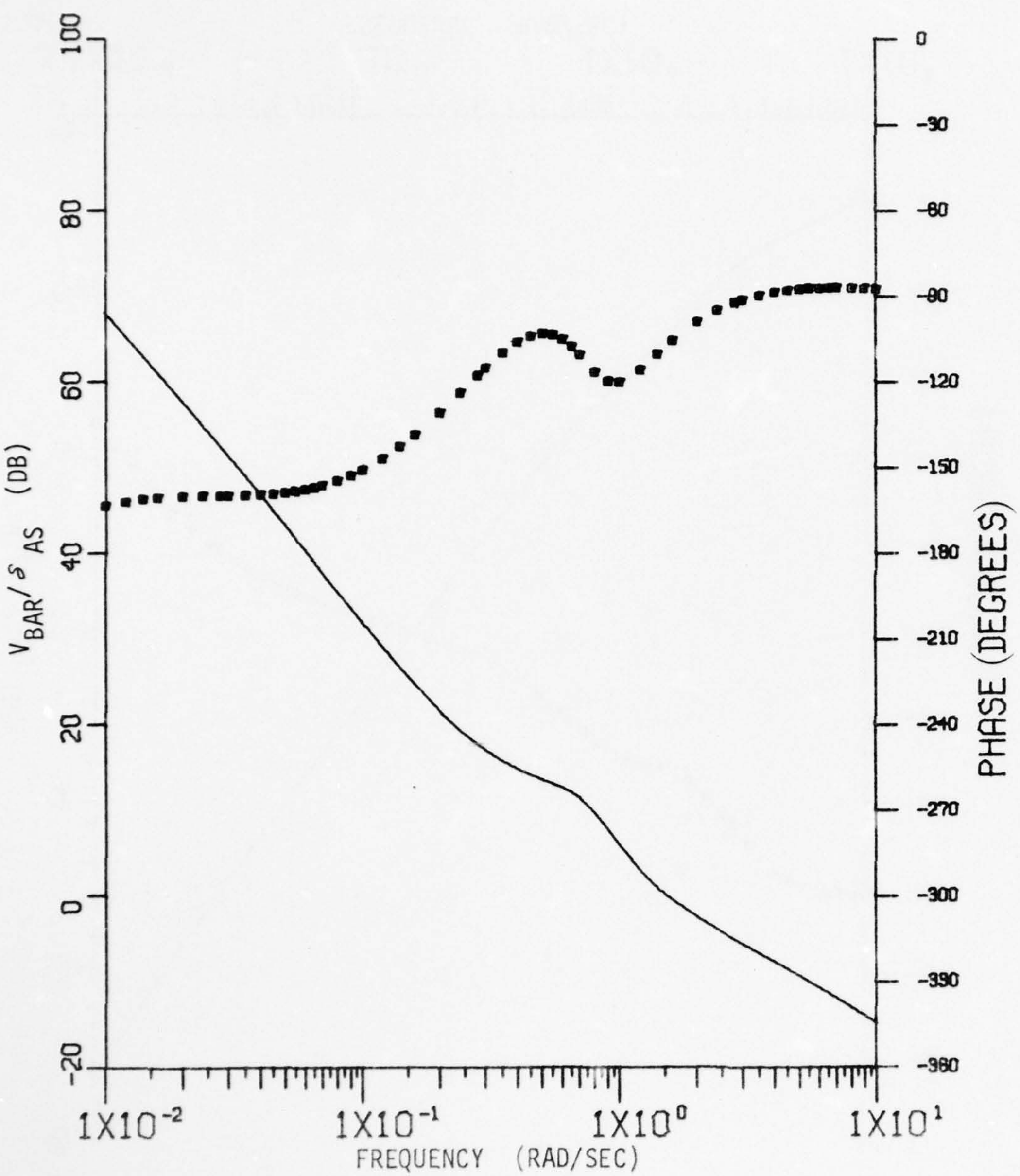


Figure I-7(c)(Cont) 65 KNOTS (ATC) V_{BAR}/δ_{AS} BODE PLOT

65 KNOTS (ATC)

(v) RCAH 2 F-169/AV8-3

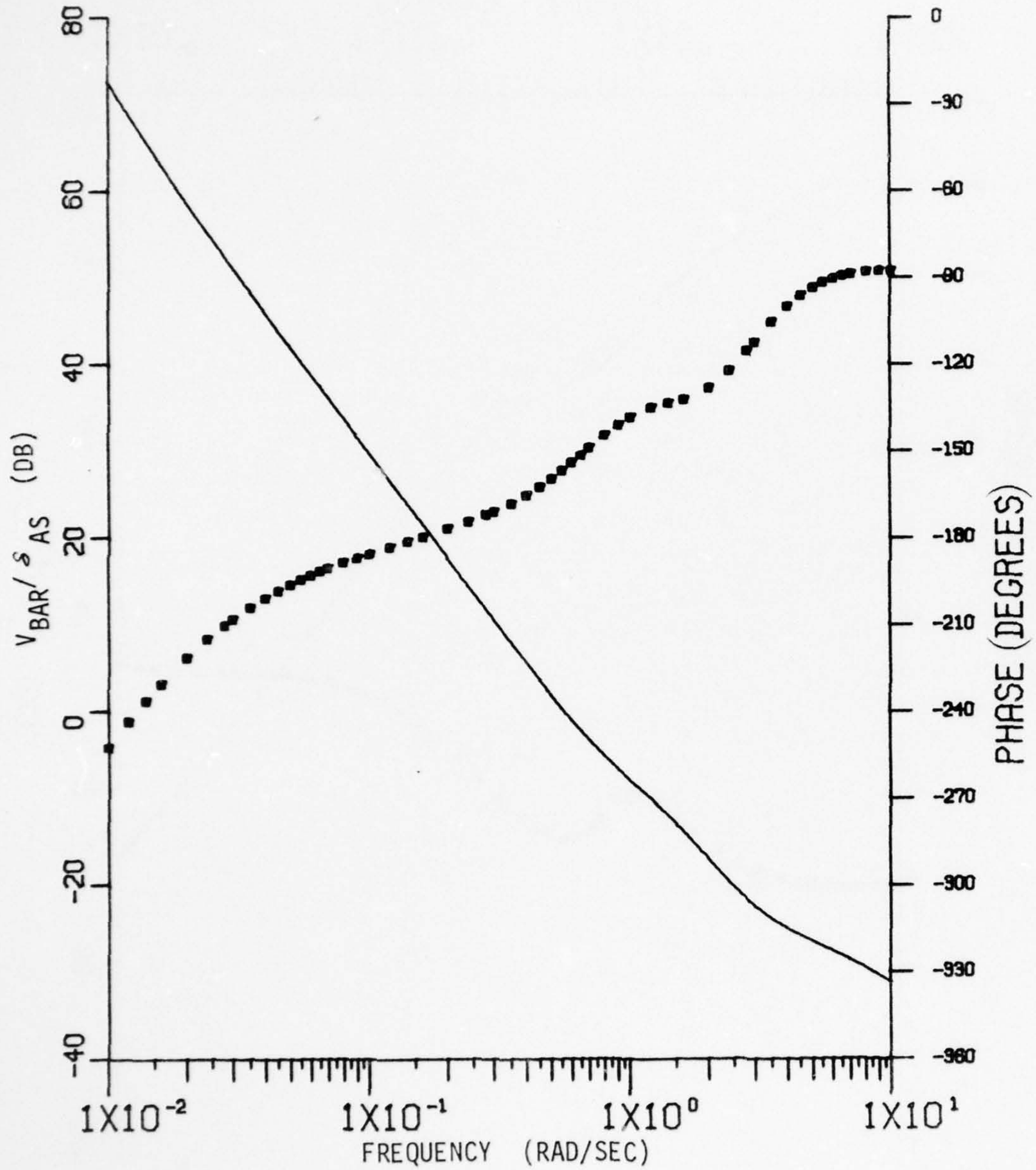


Figure I-7(c)(Cont) 65 KNOTS (ATC) V_{BAR}/δ_{AS} BODE PLOT

65 KNOTS (ATC)

(vi) ACAH 1 F-164/AV8-6

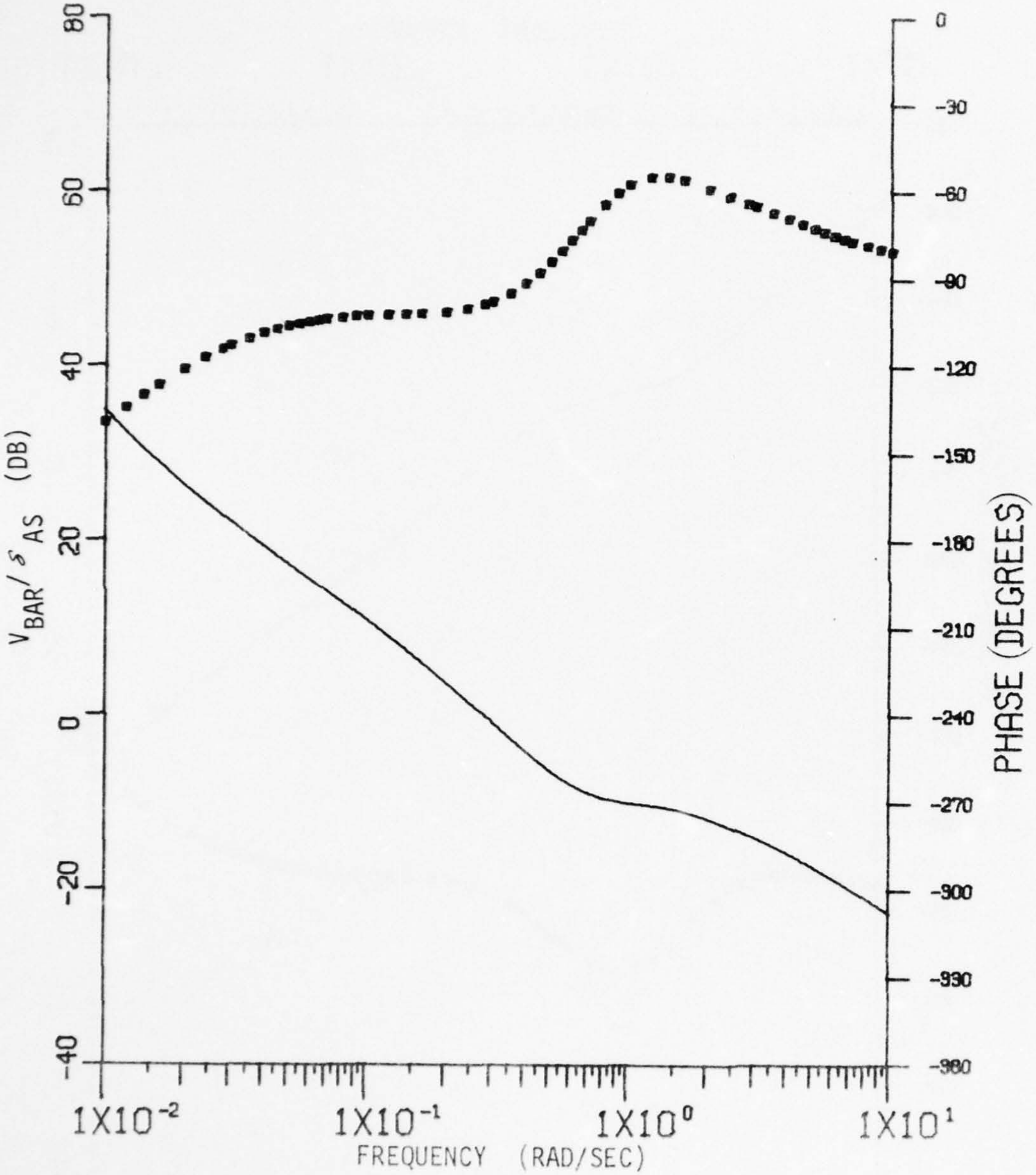


Figure I-7(c)(Cont) 65 KNOTS (ATC) V_{BAR}/δ_{AS} BODE PLOT

65 KNOTS (ATC)

(vii) ACAH 1 F-165/ED2-2

ACAH 1.5 F-159/AV8-0

F-160/AV8-0

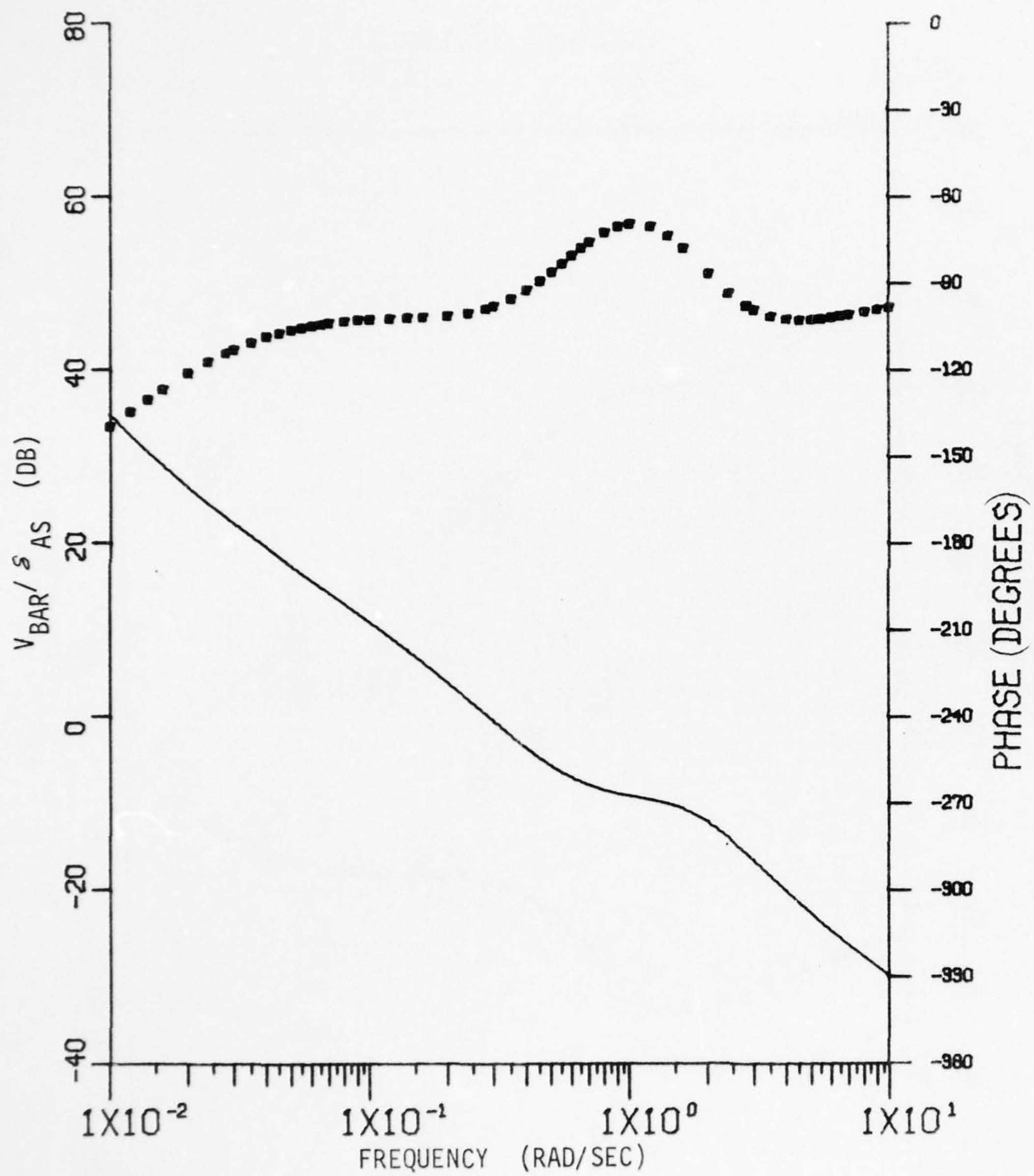


Figure I-7(c)(Cont) 65 KNOTS (ATC) V_{BAR}/δ_{AS} BODE PLOT

65 KNOTS (ATC)

(viii) ACAH 1 F-166/AV8-6
F-180/ED2-2

ACAH 1.5 F-179/AV8-0
F-179/AV8-3

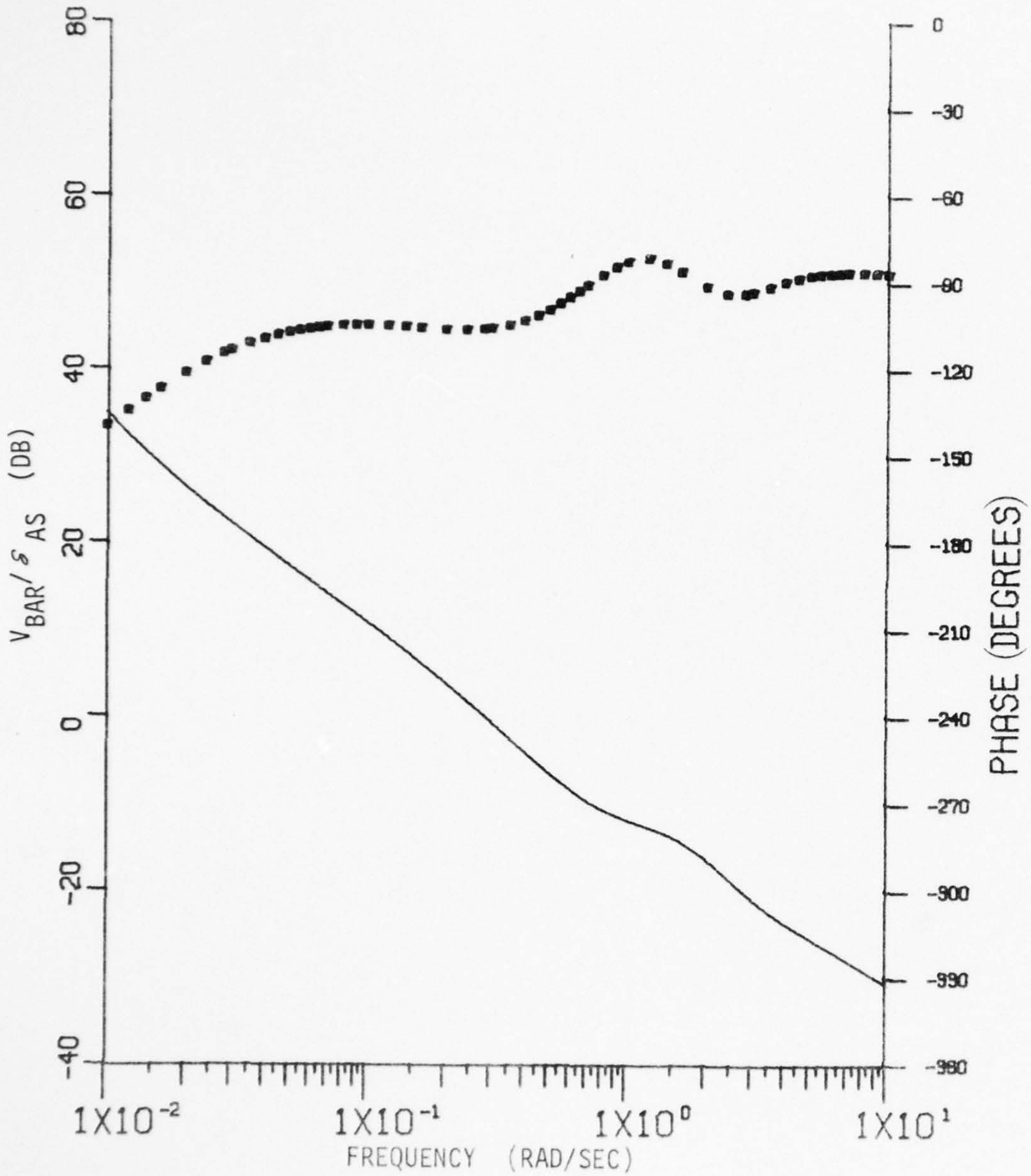


Figure I-7(c)(Cont) 65 KNOTS (ATC) V_{BAR}/δ_{AS} BODE PLOT

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APPENDIX II
PILOT COMMENTARY

Summaries of all the pilot comments for the configurations evaluated in this experiment are presented in this appendix. These summaries were prepared from transcriptions of the tape-recorded comments made by the pilot at the conclusion of each evaluation as was discussed in Section 7 of this report. With respect to the Pilot Comment Card presented in Section 7.6, the summaries correspond directly to the major headings on the card; answers to some of the detailed questions (e.g. Aircraft Response particulars) are, however, grouped under the major heading only instead of being separated.

The comments as presented here are either direct quotations or minor paraphrasings of the actual transcriptions. In cases where it might not be clear from the recorded comments exactly what the pilot meant, explanatory editorial phrases are included in parentheses for clarity.

The table at the top of each page of comments gives the control system and display presentation implemented for the evaluation. As discussed in Section 7.6, the pilot assigned three pilot ratings for each evaluation configuration. These are summarized in the table as: initial rating/final rating, turbulence rating/rating with hover excluded.

CONTROL SYSTEM:	1.0 ACAH	PILOT RATING:	3/3/3
SAS LIMITS:	UNLIM	BREAKOUT:	No
CONTROL SENS.:	.23/1.54	FLIGHT NO.:	F-158
DISPLAY:	ED2-0		

GENERAL: Any problems were with pitch control, roll not a problem except in hover, when you fly it sideways you really feel the side acceleration.

APPROACH PERFORMANCE:

- INTERCEPT: Not difficult. Height control good.

- TRACKING: Could do as well as desired. Tendency to have to work harder on speed control around 20-40 kt.

- HOVER: Excellent. A little hard to get used to side acceleration. Breakout wouldn't make any difference.

AIRCRAFT RESPONSE: Roll good. Pitch minor problem with trim. Directional not a factor. Height control excellent. Longitudinal velocity control satisfactory. Turbulence noticeable but not really a problem.

DISPLAY CHARACTERISTICS: No problems. Excellent.

SUMMARY: Same rating without hover. A little extra workload at 30-40 kt.

AD-A068 818 CALSPAN CORP BUFFALO N Y F/G 1/3
AN EXPERIMENTAL INVESTIGATION OF CONTROL-DISPLAY REQUIREMENTS F--ETC(U)
JUL 78 J V LEBACQZ, R C RADFORD, J L BEILMAN N62269-76-C-0370
UNCLASSIFIED CALSPAN-AK-5985-F-1 NADC-76099-60 NL

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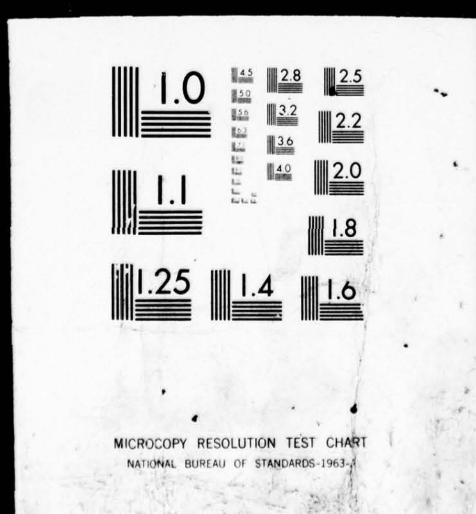


CONTROL SYSTEM:	AVSAS	PILOT RATING:	7/7/4
SAS LIMITS:	UNLIM	BREAKOUT:	NO
CONTROL SENS.:	.23/.5	FLIGHT NO.:	F-158
DISPLAY:	AV8-0		

GENERAL: Get lost in hover, performance not adequate, don't have sufficient information. Major problems with display in hover.

APPROACH PERFORMANCE:

- INTERCEPT: Good once I got used to using throttle for vertical motions of director.

- TRACKING: Satisfactory before nozzle change. After, uneasiness as to where you were, what speed you were at. No sense of tracking velocity.

- HOVER: Got there by luck. Breakout would help, should be for last 30 kt.

AIRCRAFT RESPONSE: No complaints pitch, roll, directional. Height control deteriorated in hover. Lost feel for velocity control half way through transition. Turbulence noticeable but no extra workload.

DISPLAY CHARACTERISTICS: Hard to get used to flight director. Problem at low speed not knowing where I am relative to the pad. Don't know where the hell I'm at because the velocity I get [on this display] is not relative to the ground.

SUMMARY: If exclude hover and last 30 kt, give it a 4 because I don't like the display.

CONTROL SYSTEM:	2.0 RCAH	PILOT RATING:	3/2½/-
SAS LIMITS:	UNLIM	BREAKOUT:	NO
CONTROL SENS.:	.23/1.54	FLIGHT NO.:	F-158
DISPLAY:	AV8-5		

GENERAL: Minor oversensitivity in roll in initial part of approach, some deterioration tracking localizer. Velocity vector too small in hover to be useful.

APPROACH PERFORMANCE:

- INTERCEPT: Oversensitivity in roll is nit picking problem.

- TRACKING: Good, particularly after nozzle change. Velocity tracking good.

- HOVER: No problems. Don't really have precise sense of pitch attitude with this ladder display and the gaps in the pitch bars.

AIRCRAFT RESPONSE: Pitch good. Initial roll response high, predictability good. No directional problems. Thrust very good, precise control. Velocity control good, could stabilize pitch in spite of attitude display deficiency. Turbulence not a problem.

DISPLAY CHARACTERISTICS: Mild deficiency with pitch information, not a problem with this airplane.

SUMMARY: Last half of approach so good will up initial rating by 1/2. Excluding hover would make no difference.

CONTROL SYSTEM:	1.5 ACAH	PILOT RATING:	7/7/3
SAS LIMITS:	UNLIM	BREAKOUT:	NO
CONTROL SENS.:	.23/1.8	FLIGHT NO.:	F-160
DISPLAY:	AV8-0		

GENERAL: Major problem was display, lack of information, inadequate direction as to pitch attitude commands. Major problem in hover, no idea where [hover] spot is, height control performance gets shabby as I concentrate on where spot is. Contributing factor is flight director is not doing the job at low speed.

APPROACH PERFORMANCE:

- INTERCEPT: Not a problem.

- TRACKING: Satisfactory prior to deceleration. Deteriorated during deceleration as I lacked necessary information.

- HOVER: Combination of height control and velocity tracking too much for me with display I had. Was not really possible to stabilize in hover. Breakout would certainly help, say at 100 ft [AGL] would make a tremendous difference.

AIRCRAFT RESPONSE: No problem; pitch, roll good, directional no problem. Height control itself not problem, just workload in hover caused deterioration because of lack of information. Velocity tracking unsatisfactory, unacceptable at low speed and hover. Turbulence not a factor.

DISPLAY CHARACTERISTICS: No intrepretation problems, [2-axis] flight director a little strange to fly, but can get used to it and do precise job during initial part of approach. Command information not satisfactory in latter stages of approach.

SUMMARY: It is controllable, adequate performance not attainable if you include hover, I agree with my initial rating. Would be improved with breakout at 100 ft AGL, could have adequate performance, would be satisfactory but require compensation because of display attitude information.

CONTROL SYSTEM:	1.0 RCAH	PILOT RATING:	5/5/5
SAS LIMITS:	UNLIM	BREAKOUT:	NO
CONTROL SENS.:	.23/1.8	FLIGHT NO.:	F-160
DISPLAY:	AV8-5		

GENERAL: Noise in display caused uneasiness. Trim changes during initial part of transition gave me trouble in getting it settled down. Didn't seem to get last increment in nozzle (duct) rotation, had to hold really uncomfortable nose-high attitude in hover to stay in position: had trouble with pitch attitude in hover.

APPROACH PERFORMANCE:

- INTERCEPT: No problem.

- TRACKING: Good before nozzle change. After, had trouble with pitch attitude control in combination with height control. Once trim change organized then velocity tracking reasonable except for nose high attitude required in hover. Some inaccuracies because of display, heading information jumping around changing digits, contributed to accuracy problem.

- HOVER: Could get it stabilized, did not tend to overshoot in spite of having to hold nose so high. Breakout would help only if could do it well above initial part of transition to help with trim changes.

AIRCRAFT RESPONSE: Pitch control a problem because had to chase large trim change. I could do it, but was high work load. Directional no problem. Some difficulty with height control getting organized in latter stages of transition: if I could pay attention, I could do it properly. Velocity control not satisfactory because of nose high attitude required to stop it in hover. Turbulence not a factor.

DISPLAY CHARACTERISTICS: Noise a problem, was a factor in evaluation. Format excellent, good information.

SUMMARY: Some feeling of confusion if you get large errors built up, not confortable, unsatisfactory. Transition trim changes bothered me most. Agree with initial rating. Don't think breakout for hover would change it - need breakout before transition, which I don't think is what you mean.

CONTROL SYSTEM:	AVSAS	PILOT RATING:	5½/5½/5½
SAS LIMITS:	UNLIM	BREAKOUT:	NO
CONTROL SENS.:	.23/.50	FLIGHT NO.:	F-162
DISPLAY:	AV8-5		

GENERAL: Turbulence caused major problems. Ball motion in turbulence led to difficulty tracking localizer; quite uncomfortable in approach, better in hover. Display lacking in precision with which you can judge pitch attitude, airspeed bounding around made more of a requirement to control pitch attitude and it was more difficult to do so.

APPROACH PERFORMANCE:

- INTERCEPT: Unsatisfactory, could not hold it on localizer, some problems with display settling down. Glideslope no problem.

- TRACKING: Unsatisfactory before nozzle change; could not get heading down. Directional excursions of ball gave feeling of discomfort in cockpit. First part of transition very uncomfortable. Was in a good crosswind, disconcerting accelerations in cockpit. Velocity tracking unsatisfactory, partly due to turbulence and partly due to display of attitude with this format.

- HOVER: Aircraft much smoother, better when I switched to heading hold in hover. Hover satisfactory, could achieve desired location, could place it where I wanted. No tendency to overshoot, stabilization not a problem. Had to hold nose down a fair way, but that's not as difficult as nose up. Breakout would not help - hover was best part.

AIRCRAFT RESPONSE: Airplane well behaved in roll, some lack of precision of trim in pitch. Couldn't discern directional coordination problem but there were lots of ball excursions. Thrust control good. Turbulence inputs a major factor prior to hover.

DISPLAY CHARACTERISTICS: No interpretation problems. Lack of precision in pitch with this type of format. Command information was satisfactory but took a long time to settle down [after intercept of MLS beam].

SUMMARY: Controllable, could get the job done, not happy, it is moderately objectionable. Agree with initial rating. Rating would be same if you exclude the hover.

CONTROL SYSTEM:	1.5 ACAH	PILOT RATING:	4/4/4
SAS LIMITS:	Unlim	BREAKOUT:	No
CONTROL SENS.:	.23/1.8	FLIGHT NO.:	F-162
DISPLAY:	ED2-0		

GENERAL: Turbulence very bad today, hard to take into account. Major problems associated with turbulence and roll response. Jerky in roll, tended to overcontrol, holding force in steady turns was a pain in intercept.

APPROACH PERFORMANCE:

- INTERCEPT: Satisfactory once it got established and could use smooth inputs. Lateral forces for steady turns a pain.

- TRACKING: Tended to be jerky after the nozzle change, but the wind, cross-wind, and turbulence make noise horrendous after the deceleration and that is a big factor. Velocity tracking a problem because winds seemed to make it decelerate too quickly, blew it back off pad.

- HOVER: Well behaved. Problem getting to pad because of winds. Breakout would not significantly help airplane.

AIRCRAFT RESPONSE: Roll abrupt on initial response, had to hold heavy forces in steady state. Pitch I don't remember: this display is excellent for discerning required small pitch changes to keep track of pitch. Directional no problems noted except turbulence. Thrust satisfactory, tend to drop down a little bit right on last part of level-off. Velocity control would be very good on a decent day, was satisfactory.

DISPLAY CHARACTERISTICS: Excellent. Really like pitch attitude precision with this format.

SUMMARY: Minor but annoying deficiencies centered around roll control, turbulence today forces me into unsatisfactory category. Agree with initial rating. If hover removed rating would be unchanged.

CONTROL SYSTEM:	1.0 RCAH	PILOT RATING:	3/3/3
SAS LIMITS:	UNLIM	BREAKOUT:	NO
CONTROL SENS.:	.23/1.8	FLIGHT NO.:	F-162
DISPLAY:	AV8-5		

GENERAL: Weird anomalies because of very strong winds, turbulence. Aircraft a little too sensitive in pitch and to some extent in roll. Could fly smoothly but had to be delicate. Don't like the pitch presentation with this display, would like to be able to get reference chevrons where I want.

APPROACH PERFORMANCE:

- INTERCEPT: Not a problem.

- TRACKING: Localizer, glide slope no problem before nozzle change. Have tendency to decelerate too quickly after nozzles: have to keep nose down in these winds. Although got off on airspeed, have perfect control of what was going on. Crosswind makes drift problem.

- HOVER: Well behaved, could achieve desired conditions. In these strong winds, have to take extra time. When move laterally in heading the cockpit side loads are very weird today. Breakout would not change rating.

AIRCRAFT RESPONSE: Initial pitch response a little abrupt, but predictable, sensitivity seemed okay. Roll pretty snappy, probably on upper limits of what you would like, no directional problems noted except turbulence, crosswinds. Was constantly a little behind thrust control, but in general it was satisfactory. Velocity control satisfactory in context of wind we had, extreme nose down attitude required. Turbulence inputs a major factor throughout approach.

DISPLAY CHARACTERISTICS: No interpretation problems, still don't like pitch attitude presentation. Sensitivitives ok. Command information satisfactory, can use it adequately in hover. Velocity vector and diamond make sense.

SUMMARY: Controllable, adequate, satisfactory with mildly unpleasant deficiencies. Agree with initial rating. Rating would not change if hover not included.

CONTROL SYSTEM:	AVSAS	PILOT RATING:	7/7A/4→5
SAS LIMITS:	AV-8B	BREAKOUT:	NO
CONTROL SENS.:	.23/.50	FLIGHT NO.:	F-163
DISPLAY:	AV8-5		

GENERAL: Controllable but could not achieve adequate performance because directional got messed up midway through transition. Got cross control, hard to get ball in center, very uncomfortable, detracted from performance elsewhere. Roll attitude doesn't come through well with this display and had to pay attention to it with this airplane.

APPROACH PERFORMANCE:

- INTERCEPT: Localizer moved back and forth more than is satisfactory because of lack of precision in roll. Glide slope no problem.

- TRACKING: Lateral errors got large after nozzle change because of increased difficulty of directional control. Velocity tracking deteriorated because of lateral loads, attention required.

- HOVER: Could stabilize aircraft nicely once I got to heading hold. Could achieve satisfactory performance. Breakout would have to be high--say 200 feet--to help with directional problem. Hover was ok.

AIRCRAFT RESPONSE: Pitch satisfactory, predictable, had to pay attention to it to achieve attitude I wanted. Roll sensitivity seemed low, seemed to leave bank angles in and have trouble with localizer. Directional had no coordination problems in initial phases of approach, but was very uncomfortable and high workload in latter stages of transition. Thrust control satisfactory, no cross coupling. Turbulence not a factor at all.

DISPLAY CHARACTERISTICS: No interpretation problems. Do not like the pitch ladder. Sensitivities ok, command information satisfactory.

SUMMARY: Controllability not in question, but could not achieve adequate performance. If removed hover only, would not change, but would be a 4 or 5 if breakout at 200 feet.

CONTROL SYSTEM:	1.0 RCAH	PILOT RATING:	5/5A/5
SAS LIMITS:	AV-8B	BREAKOUT:	NO
CONTROL SENS.:	.23/1.8	FLIGHT NO.:	F-163
DISPLAY:	AV8-5		

GENERAL: Oversensitive in roll, over controlled in roll at hover. Feeling of reasonable confidence with airplane.

APPROACH PERFORMANCE:

- INTERCEPT: Localizer: could do the job. Sensitive airplane--felt as if should fly with fingertips. Trouble with glideslope on second approach, but was poor set-up. Generally satisfactory.

- TRACKING: Localizer satisfactory before nozzle change, very sensitive after but performance satisfactory. Tendency to overcontrol in pitch also - too sensitive.

- HOVER: Could settle it down and get satisfactory performance, but roll control too sensitive. Breakout would not affect.

AIRCRAFT RESPONSE: Initial response predictable, but sensitivity too high in pitch, some problem with roll sensitivity in hover. Directional not a factor. Thrust satisfactory - problem on second approach probably due to initial conditions. Turbulence noticeable at altitude but not factor.

DISPLAY CHARACTERISTICS: Don't like pitch ladder, but chevrons do help with pitch precision. Do not like bank attitude display, don't know what bank angle I'm at.

SUMMARY: Controllable, adequate performance, but not satisfactory. Question is whether desired performance could be achieved. Removing hover would not change rating.

CONTROL SYSTEM:	1.0 ACAH	PILOT RATING:	3/3A/3
SAS LIMITS:	AV-8B	BREAKOUT:	No
CONTROL SENS.:	.23/1.80	FLIGHT NO.:	F-163
DISPLAY:	ED2-0		

GENERAL: A little sensitive, minor tendency to overcontrol. Contending with pitch altitude changes during last part of approach was weird -- aircraft seemed sensitive in initial response but sensitivity low at that latter stage, seemed to have to make large inputs.

APPROACH PERFORMANCE:

- INTERCEPT: Satisfactory, about as good as I wanted. Roll perhaps sensitive, tendency to wallow on localizer.

- TRACKING: Satisfactory before nozzle change. After, some learning to make necessary stick inputs to control speed, but had very precise control of the display of pitch altitude. Could move line-widths and control velocity that way.

- HOVER: Could control as precisely as desired. Breakout would make no difference.

AIRCRAFT RESPONSE: Pitch initial response satisfactory, predictable enough, sensitivity seemed low in last part of transition. Could really stabilize with this display as opposed to last one (AV8-5). Roll sensitivities a little high, not as solid as desired. Directional not a factor. Thrust control good. Turbulence not really noticed, not a problem.

DISPLAY CHARACTERISTICS: No problem -- would like some of digital readouts nearer center. Really do like altitude display, easy to avoid overcontrol.

SUMMARY: Controllable, adequate performance, satisfactory with minor reservations. Removing hover would not change rating. Turbulence did not affect evaluation.

CONTROL SYSTEM:	AVSAS	PILOT RATING:	7/7A/7
SAS LIMITS:	AV-8B	BREAKOUT:	NO
CONTROL SENS.:	.23/.50	FLIGHT NO.:	F-164
DISPLAY:	ED2-2		

GENERAL: Display didn't make sense to me. Couldn't do job because of discrepancy between control director and position display. Some problem trimming aircraft directionally. Crosswind noticeable at end.

APPROACH PERFORMANCE:

- INTERCEPT: Localizer ok using director. Glide slope started high, some problems with throttle director, but satisfactory.

- TRACKING: Localizer satisfactory before nozzle damage, although needles didn't seem quite right, they're responsive to turbulence, bounce around. Glideslope satisfactory before nozzle change once I got there. Problems with crosswind after nozzle change. Discrepancy between pitch command and my position made velocity tracking difficult.

- HOVER: Satisfactory once settled down, could center needles and they brought me to pad but didn't seem to be working properly, couldn't rely on them. Breakout would make no difference.

AIRCRAFT RESPONSE: Directional problems with initial trim, crosswind at end. Thrust control satisfactory, display brought me to 80 feet though. Velocity control not satisfactory in total context. Turbulence not a problem except jiggled vertical bar on flight director.

DISPLAY CHARACTERISTICS: Control directors didn't seem right.

SUMMARY: Cannot achieve adequate performance with tolerable pilot workload. Would not change without hover. Turbulence not a factor, although crosswind was.

CONTROL SYSTEM:	1.0 RCAH	PILOT RATING:	6/6D/4½
SAS LIMITS:	AV-8B	BREAKOUT:	NO
CONTROL SENS.:	.23/.99	FLIGHT NO.:	F-164
DISPLAY:	ED2-0		

GENERAL: Want to make it a better airplane than the performance I could achieve. Get screwed up down into hover because of extreme nose high attitudes required. Tailwind component with crosswind a major problem, some problems with display. Aircraft responsive to transients in pitch, difficult to trim.

APPROACH PERFORMANCE:

- INTERCEPT: Good.

- TRACKING: Localizer satisfactory before nozzle change. Glide slope adequate before nozzles. Pitch transients after nozzle change noticeable, responsiveness to turbulence bothersome. Really had to work on velocity tracking near end, could barely achieve performance even though had good feeling of control.

- HOVER: Difficult to stabilize, approach path gets off and get screwed up wanting to slide over and face wind. Breakout would certainly help.

AIRCRAFT RESPONSE: No problems in roll. Pitch seemed to be drifting in trim, transients, responsive to turbulence. Could achieve predictable attitudes if I had time to look at it. Directional not a factor. Thrust control could do job if could watch it, but did get off hover height while concentrating on lining up and getting over pad. Longitudinal velocity control not satisfactory in latter stages. Turbulence a factor in pitch.

DISPLAY CHARACTERISTICS: I like this display. No objections.

SUMMARY: Controllable, barely adequate performance. Would go to 4-1/2 if broke out at 200 feet. Turbulence did not compromise but did affect evaluation, noticeable.

CONTROL SYSTEM:	1.0 ACAH	PILOT RATING:	4/4B/4
SAS LIMITS:	AV-8B	BREAKOUT:	No
CONTROL SENS.:	.23/.50*	FLIGHT NO.:	F-164
DISPLAY:	AV8-6		

*Mistake in set-up card.

GENERAL: Problems with wind in hover. Roll forces in hover were very high, pitch seemed too sensitive, although predictable and could follow flight director.

APPROACH PERFORMANCE:

- INTERCEPT: Localizer no problem, glideslope no problem. Flight director good.

- TRACKING: Satisfactory before nozzles. Jumpiness in pitch right at nozzle change required extra control activity. Velocity tracking ok once I forced myself to follow flight director but really had to get nose up.

- HOVER: No tendency to overshoot, could stabilize. Lateral corrections a problem, heading wandering, high forces, felt as if I were cross-controlling, really felt side loads.

AIRCRAFT RESPONSE: Roll sensitivity too low, forces too high. Initial response and predictability all right. Pitch response a bit fast initially, too sensitive, but predictable. No directional problems up and away, but problems at end in heading hold. Thrust control satisfactory, could get good cross check on display. Velocity control not quite satisfactory because of transients. Turbulence not noticed.

DISPLAY CHARACTERISTICS: Flight director made sense, well behaved, correlated with situation display. Still didn't like this pitch ladder, seemed bouncy.

SUMMARY: Could do job, not happy with lateral forces or bounciness in pitch. Would not change without hover. Turbulence didn't really affect it but wasn't zero -- light, negligible effect on performance.

CONTROL SYSTEM:	AVSAS	PILOT RATING:	5/5½C/5½
SAS LIMITS:	AV-8B	BREAKOUT:	NO
CONTROL SENS.:	.23/.50	FLIGHT NO.:	F-165
DISPLAY:	AV8-6		

GENERAL: Directional coordination at end a big problem. Flight director not good: wanders around, is noisy and not solid enough, doesn't make sense during last part of approach. Directional cross-control right at start of transition and at end is very disconcerting, directional workload high.

APPROACH PERFORMANCE:

- INTERCEPT: Bad on both approaches. Watched lateral so long on first that I missed glideslope entirely. Glide slope ok on second but had system problems with new localizer course and localizer was bad.

- TRACKING: Couldn't track localizer after nozzle change. Really had problems with my feet, drifted to right all the time. Velocity tracking a problem.

- HOVER: Well behaved in hover. Is one of better features, so breakout wouldn't help.

AIRCRAFT RESPONSE: Pitch and roll satisfactory, some pitch workload at nozzle change. Could sustain bank angle. Directional really a problem in latter stages of transition. Thrust satisfactory, longitudinal velocity compounded by directional problems, turbulence noticeable but not factor.

DISPLAY CHARACTERISTICS: Flight director sensitivity reasonable [?-author], would like pitch bars to go all the way across.

SUMMARY: Barely adequate performance. [No hover rating, but previous comment indicates it would be same].

CONTROL SYSTEM:	AVSAS	PILOT RATING:	6/6D/-
SAS LIMITS:	AV-8B	BREAKOUT:	NO
CONTROL SENS.:	.23/.50	FLIGHT NO.:	F-165
DISPLAY:	AV8-3		

GENERAL: Hard to judge performance in hover because don't know where the hell pad is. Am not happy with flight director: jittery and erroneous, large excursions not caused by me, confidence in it very low. Tendency to over control in pitch at nozzle rotation. Directional coordination also a problem

APPROACH PERFORMANCE:

- INTERCEPT: Could do localizer, but had to interpret jumpy flight director. Got preoccupied with lateral, missed glide slope on both approaches.

- TRACKING: Glide slope seemed ok, paid most of attention to lateral command and which way to turn. Could do it before nozzles but not satisfactory. Could barely achieve adequate performance after nozzles: pitch transients and concern about the ball. Velocity tracking not satisfactory but adequate.

- HOVER: Better airplane in hover, but hard to judge performance. Breakout would help, but also need better flight director.

AIRCRAFT RESPONSE: Roll satisfactory pitch sensitivity high, tendency to overcontrol pitch. Directional ok initially, but got hung up with ball out in latter part, didn't make sense. Thrust satisfactory - performance not too good because of distractions elsewhere. Longitudinal velocity control not satisfactory.

DISPLAY CHARACTERISTICS: Concerned about pitch accuracy, discriminating small pitch changes with this format. Do not like not having position status information, especially with this flight director.

SUMMARY: Could stumble my way down and get stopped, yet would like to degrade it because of dependence on flight director which isn't credible. Don't like words that go with 7 however, [no rating given for excluding hover]. Turbulence affected evaluation. Am calling it controllable, get yet confused when display doesn't give enough information to judge performance.

CONTROL SYSTEM:	1.0 ACAH	PILOT RATING:	4/4-/4
SAS LIMITS:	AV-8B	BREAKOUT:	No
CONTROL SENS.:	.23/.50	FLIGHT NO.:	F-165
DISPLAY:	ED2-2		

GENERAL: High lateral forces a deficiency, seemed to ruin good airplane.

APPROACH PERFORMANCE:

- INTERCEPT: Localizer marred by high lateral stick forces. Glidescope not a problem, some sliding back and forth with flight director but had confidence.

- TRACKING: Very stable roll nice for tracking, just follow flight director, both before and after nozzles. Pitch bar seemed to jump a little, but minor. Velocity tracking after nozzles satisfactory. A little hunting on glideslope.

- HOVER: Flight director bringing us to 80 ft. Hover pleasant, no overshoot, could be as accurate as desired. Only problem was counteracting crosswind from left, required high lateral force. Breakout would make no difference.

AIRCRAFT RESPONSE: Pitch well behaved, predictable, good sensitivities. Roll good on approach, but sensitivity low for gross maneuvering, very stable however. No directional difficulty on approach, nothing bothersome, am paying more attention to heading. In hover had to hold two ball widths off to side to hold position. Thrust control some tendency to overcontrol following director. Longitudinal velocity control satisfactory. Turbulence jarred airplane but didn't affect performance.

DISPLAY CHARACTERISTICS: Stable airplane means I didn't have to use pitch altitude, but control directors so far away from primary pitch reference that could be scan problem if I had to use it.

SUMMARY: Lateral forces only problem -- change gearing and it might be a 2. Controllable, could achieve desired performance. [No rating for hover breakout, but comments indicate it would be same.] [No turbulence rating.]

CONTROL SYSTEM:	AVSAS	PILOT RATING:	4/4B/4
SAS LIMITS:	AV-8B	BREAKOUT:	NO
CONTROL SENS.:	.23/.50	FLIGHT NO.:	F-166
DISPLAY:	AV8-6		

GENERAL: Height flight director never really settled down, other directors seem a little jittery.

APPROACH PERFORMANCE:

- INTERCEPT: Localizer easy with flight director. Glideslope seem to be chasing the index all the time, seems to be some pitch-throttle coupling during initial part.

- TRACKING: Satisfactory before nozzle change. Only problem after change was learning to turn into wind. Velocity tracking good once you got turned.

- HOVER: Well behaved, very responsive. Breakout would not help.

AIRCRAFT RESPONSE: Pitch no complaints, smooth and predictable. Roll satisfactory. Directional only a problem contending with crosswind at end, but works well if you turn into wind before going to heading hold. Thrust control seemed to spend a lot of time getting circle on index, would rather just have raw information. Longitudinal velocity control satisfactory. Didn't notice turbulence.

DISPLAY CHARACTERISTICS: Flight directors a little jittery, chevrons really help on approach.

SUMMARY: Height control not satisfactory and flight director jitteriness warrant improvement. Without hover it wouldn't change, turbulence light with negligible effect.

CONTROL SYSTEM:	AVSAS	PILOT RATING:	5/5B/5
SAS LIMITS:	AV-8B	BREAKOUT:	NO
CONTROL SENS.:	.23/.50	FLIGHT NO.:	F-166
DISPLAY:	ED2-1		

GENERAL: Everything fine on approach and in hover, but getting everything organized at end when deceleration is almost over is high work load item. Display reasonable.

APPROACH PERFORMANCE:

- INTERCEPT: No problem.

- TRACKING: Good as you wanted before nozzle change. Tracking of localizer is major difficulty after nozzle change. Velocity tracking reasonably precise once you get that transient [near the level off] out of the way.

- HOVER: Very easy to fly on heading hold, didn't have to turn around much. Very stable, display excellent in that area. Breakout would make no difference.

AIRCRAFT RESPONSE: Roll satisfactory. Seemed to make large pitch changes, working in pitch a lot, but I don't really think pitch itself a problem. Directional no coordination problems on approach, some at last part of transition getting the ball organized. Thrust control, display wanders around too much. Longitudinal velocity satisfactory except for that short time in middle of transition. Turbulence inputs noticeable, side loads noticeable, crosswinds seem to give me problem.

DISPLAY CHARACTERISTICS: Like velocity vector, like pitch attitude, command information satisfactory [except throttle director].

SUMMARY: Controllable, adequate performance was all I could achieve. Turbulence noticed, didn't really affect evaluation. [No hover rating given, but comments indicate it wouldn't change].

CONTROL SYSTEM:	1.0 ACAH	PILOT RATING:	4/4C/4
SAS LIMITS:	AV-8B	BREAKOUT:	No
CONTROL SENS.:	.23/1.80	FLIGHT NO.:	F-166
DISPLAY:	AV8-6		

GENERAL: Flight director commanded too large pitch excursions, seemed unwarranted. Roll sensitivity high, fingertip operation. Had to make large pitch inputs in last part of transition, turbulence also noticeable.

APPROACH PERFORMANCE:

- INTERCEPT: Satisfactory. Height control seemed better, maybe I am anticipating it.

- TRACKING: Satisfactory before nozzle change. Workload problem in pitch after change. Could not zero flight director commands -- didn't want to put in such large pitch. Flight director seemed to move around, but not at high frequency as before.

- HOVER: Flight director not terribly precise, but could find way to center of approach pad using situation display: no problem, satisfactory. Hover is quite good. Breakout wouldn't make any difference.

AIRCRAFT RESPONSE: Pitch smooth, responsive, predictable. Roll sensitivity on high side, seemed like fighter airplane in hover. No directional problems, were approaching into wind. Don't like throttle director for throttle control. Longitudinal velocity high workload but could do it. Turbulence noticeable in pitch.

DISPLAY CHARACTERISTICS: Noise in flight director. Information precise enough except for hover.

SUMMARY: Controllable, could do job, moderate workload to achieve desired performance. Excluding hover would not change rating. Turbulence noticeable, minor effect on performance.

CONTROL SYSTEM:	AVSAS	PILOT RATING:	3/3B/3
SAS LIMITS:	AV-8B	BREAKOUT:	NO
CONTROL SENS.:	.23/.50	FLIGHT NO.:	F-167
DISPLAY:	ED2-0		

GENERAL: More concerned about crosswind than had to be. Could fly with confidence. Sensitivity in altitude error display could be higher.

APPROACH PERFORMANCE:

- INTERCEPT: Satisfactory

- TRACKING: Satisfactory before nozzle change. After, I had some concern about cross-control in the crosswind, over-anticipated and made my own problems.

- HOVER: Excellent, breakout wouldn't make any differnece.

AIRCRAFT RESPONSE: Smooth and predictable in both areas (roll & pitch). Some directional concerns, but no coordination difficulty. Velocity control satisfactory. Turbulence not a factor.

DISPLAY CHARACTERISTICS: No problems, height error sensitivity could be increased.

SUMMARY: Height control in hover may not be satisfactory, but am not giving it priority in rating, is mildly unpleasant deficiency. Turbulence didn't affect. [No hover rating, comments indicate no change].

CONTROL SYSTEM:	AVSAS	PILOT RATING:	5/5C/4
SAS LIMITS:	AV-8B	BREAKOUT:	NO
CONTROL SENS.:	.23/.50	FLIGHT NO.:	F-167
DISPLAY:	AV8-0		

GENERAL: Weird, could do job in hover but felt I should be lost, seemed like fluke when we got there. Only problems were with flight director, have no assistance handling pitch altitude, seemed useless for height control. (Did three approaches).

APPROACH PERFORMANCE:

- INTERCEPT: Satisfactory

- TRACKING: Satisfactory. Just held constant attitude after nozzle change. Velocity tracking just kind of generally slowed down.

- HOVER: Could stabilize reasonably well all three times, but breakout would help feeling of apprehension.

AIRCRAFT RESPONSE: Pitch no problem, directional no problems. Flight director helped with thrust except for hover, where I just used height information. Velocity control could be changed gradually because I could stabilize pitch. Turbulence noticeable.

DISPLAY CHARACTERISTICS: Interpretation a problem, tend to confuse flight director pitch commands with height commands. Don't like it this way, would rather have help with pitch attitude. Command information unacceptable in hover.

SUMMARY: Controllable, have to say grudgingly could achieve adequate performance. Hover breakout would help, but still wouldn't like flight director [being throttle and lateral stick].

CONTROL SYSTEM:	1.0 ACAH	PILOT RATING:	4/4B/2½
SAS LIMITS:	AV-8B	BREAKOUT:	No
CONTROL SENS.:	.23/1.38	FLIGHT NO.:	F-167
DISPLAY:	AV8-5		

GENERAL: Pitch attitude sensitive, didn't like pitch display.

APPROACH PERFORMANCE:

- INTERCEPT: Satisfactory.

- TRACKING: No problem before nozzles. After, could just fly velocity vector information with good accuracy.

- HOVER: Combination of pitch sensitivity and lack of precise pitch information not satisfactory. Breakout would help with inaccuracy in positioning.

AIRCRAFT RESPONSE: Only noticed sensitivity in pitch, tendency to overcontrol, in hover. Roll stable, notice forces, generally good. No directional problems. Would like increased altitude error sensitivity on display for thrust control. Velocity control unsatisfactory in hover itself. Didn't much notice turbulence.

DISPLAY CHARACTERISTICS: Pitch altitude precision not there, chevrons help in approach where they are now, but need help in hover. Height control not really satisfactory in hover. Velocity command information very good on approach.

SUMMARY: Didn't like airplane just in hover, problems in minor category. Would be satisfactory if excluded hover. Turbulence negligible effect.

CONTROL SYSTEM:	2.0 RCAH	PILOT RATING:	4/4A/4
SAS LIMITS:	TWICE AV-8B	BREAKOUT:	No
CONTROL SENS.:	.78/.99	FLIGHT NO.:	F-168
DISPLAY:	ED2-0		

GENERAL: Too sensitive in pitch, otherwise straightforward.

APPROACH PERFORMANCE:

- INTERCEPT: Satisfactory

- TRACKING: Satisfactory before and after nozzle change except for slight tendency to overcontrol in pitch.

- HOVER: Tendency to overshoot because of having to be careful with pitch. Breakout would made no difference.

AIRCRAFT RESPONSE: Attitude responses satisfactory, pitch just too sensitive. No directional problems. Thrust control - display doesn't seem to be optimized for hover. Longitudinal velocity satisfactory but had to work a little because of sensitive controls. Turbulence not factor.

DISPLAY CHARACTERISTICS: Good. Would like range readout off to right. Rate of descent and height error don't seem optimized.

SUMMARY: Pitch sensitivity is problem, but could achieve desired performance. Turbulence not noticed. Hover (out) would made no difference.

CONTROL SYSTEM:	1.0 ACAH	PILOT RATING:	4/4A/2
SAS LIMITS:	TWICE AV-8B	BREAKOUT:	No
CONTROL SENS.:	.23/1.38	FLIGHT NO.:	F-168
DISPLAY:	ED2-0		

GENERAL: Pitch sensitivity too low. Couldn't get enough nose up at end of transition.

APPROACH PERFORMANCE:

- INTERCEPT: Satisfactory.

- TRACKING: Satisfactory except low pitch sensitivity in last part of transition.

- HOVER: Some overshoot, couldn't get nose up fast enough, large pitch changes required at end. Could eventually stabilize with good precision. Breakout would help, make it satisfactory.

AIRCRAFT RESPONSE: Pitch initial response seemed satisfactory, predictable, just low on sensitivity and that mostly showed up at end of transition. Roll satisfactory. No directional problems. Thrust, could get height organized right up to end, then look away and sink 20 or 30 feet, same pattern of errors as before. Velocity tracking unsatisfactory right at end. Turbulence noticed but not a factor.

DISPLAY CHARACTERISTICS: Would like vertical information sensitivity changed in hover. Otherwise like this format very much. Particularly like pitch attitude precision.

SUMMARY: Pitch sensitivity deficient. Would be satisfactory if removed hover.

CONTROL SYSTEM:	2.0 ACAH	PILOT RATING:	5/5A/4
SAS LIMITS:	TWICE AV-8B	BREAKOUT:	NO
CONTROL SENS.:	.78/1.38	FLIGHT NO.:	F-168
DISPLAY:	ED2-0		

GENERAL: Abrupt initial response in pitch and roll on approach, but didn't notice it in hover. Had to make large pitch changes near end of transition, couldn't make them fast enough to control position well, workload high. Trimming was big glitch in system.

APPROACH PERFORMANCE:

- INTERCEPT: Adequate performance.

- TRACKING: Adequate before nozzles, after ok until just up to edge of pad, then couldn't settle it down.

- HOVER: Tendency to overshoot, difficult to stabilize, oversensitive. Breakout would help but not make much difference because of oversensitivity.

AIRCRAFT RESPONSE: Bewildering to correlate approach [which was ok] with hover. Initial response in pitch too abrupt on approach but conversely had to move stick too far when in hover. Predictability seemed ok. Roll sensitive in approach, no problem in hover. No directional problems. Height control still problem in hover. Velocity control not satisfactory in hover, turbulence not noticeable.

DISPLAY CHARACTERISTICS: No problems.

SUMMARY: Controllable, adequate performance not attainable. [no] Hover would be 4 because still don't like sensitivity. At least crosswinds not a problem for once.

CONTROL SYSTEM:	2.0 RCAH	PILOT RATING:	3/3C/2½
SAS LIMITS:	TWICE AV-8B	BREAKOUT:	NO
CONTROL SENS.:	.23/.99	FLIGHT NO.:	F-168
DISPLAY:	ED2-0		

GENERAL: Tendency to pulse stick on approach, but might want more sensitivity in hover. Slight heaviness in pitch.

APPROACH PERFORMANCE:

- INTERCEPT: No problem.

- TRACKING: Good before nozzles, after nozzles could track velocity vector until the very end. Seem to have nose down too much on approach, have to pull back in hover, retrim which I don't want to do.

- HOVER: Tendency to overshoot but easy to overcome and stabilize. Satisfactory overall. Breakout would make little or no difference.

AIRCRAFT RESPONSE: Pitch seemed abrupt on approach but was still satisfactory, predictability satisfactory. Had lower than optimum sensitivity in hover. Roll satisfactory. No directional problems. Still need better sensitivity on display in hover for thrust. Velocity satisfactory with reservations about pitch. Turbulence noticed, affected pitch, but could contend with it.

DISPLAY CHARACTERISTICS: No problems. Want more sensitive vertical axis.

SUMMARY: Controllable, bored with giving 4's so will say it is satisfactory. Without hover, would be 1/2 rating better just to be contrary.

CONTROL SYSTEM:	2.0 RCAH	PILOT RATING:	3/3A/3
SAS LIMITS:	AV-8B	BREAKOUT:	NO
CONTROL SENS.:	.33/.99	FLIGHT NO.:	F-177
DISPLAY:	AV8-5		

GENERAL: A little extra work in pitch, not as stable as would like, tendency to drift off. Had a lot of confidence flying it.

APPROACH PERFORMANCE:

- INTERCEPT: Not a problem. Some trouble initially getting trimmed.

- TRACKING: Not a problem, wind made tracking localizer funny. No difference before or after nozzle change. Velocity tracking, I was aware of tailwind problem, got nose up early in transition. Wind made entering hover a challenge.

- HOVER: Had confidence could stabilize it even in wind. Breakout wouldn't make much difference.

AIRCRAFT RESPONSE: Roll good in all respects. Pitch trim drift a small problem, initial and final responses no complaints. Directional satisfactory. No thrust problems. Turbulence not problem, but crosswind/tailwind made for more work.

DISPLAY CHARACTERISTICS: No problems. Could put circle in diamond [vertical information]. Sensitivity satisfactory.

SUMMARY: Mildly unpleasant deficiency is need to pay a little extra attention to pitch attitude. Rating would apply without hover.

CONTROL SYSTEM: AVSAS	PILOT RATING: -/3A/3
SAS LIMITS: AV-8B	BREAKOUT: NO
CONTROL SENS.: .23/.50	FLIGHT NO.: F-177
DISPLAY: ED2-0	

GENERAL: Fathoming wind at end a problem. Airplane solid.

APPROACH PERFORMANCE:

- INTERCEPT: Not a problem.

- TRACKING: Reasonable once wind angles sorted out. Glide slope before nozzle change remarkably easy to do - circle would sit in diamond for longer periods than I remember before. No real problem after nozzle change except concern with slipping by pad because of wind. Could handle only one axis at time in velocity tracking.

- HOVER: Trouble getting to center because wind made it a two axis problem. Would get pitch organized, then try to move laterally and heading would wander, turn attention to that and screw up longitudinal. Breakout to visual wouldn't help by itself - the winds are the problem.

AIRCRAFT RESPONSE: Pitch and roll forces a little heavy but no problems in predictability. No directional coordination problems on approach, but did have some in hover trying to get over spot. Height control satisfactory, seem to be able to anticipate, circle moves to get my attention. Velocity control satisfactory in itself given the wind problems. Turbulence noticed but not a problem; crosswind a problem trying to hover on instruments.

DISPLAY CHARACTERISTICS: Some interpretation problems with change in reference system in heading hold.

SUMMARY: Adequate performance available, am not paying much weight to problems I had near the end because of the wind. Didn't notice any compensation requirements that I'd call moderate. Same rating without hover - am downgrading and not giving much weighting to gymnastics I went through in hover trying to find headings and contend with wind.

CONTROL SYSTEM:	AVSAS	PILOT RATING:	1½/1½A/1½
SAS LIMITS:	AV-8B	BREAKOUT:	NO
CONTROL SENS.:	.23/.50	FLIGHT NO.:	F-178
DISPLAY:	ED2-2		

GENERAL: Easy to fly, flight director did a good job, good conditions today.

APPROACH PERFORMANCE:

- INTERCEPT: No problem.

- TRACKING: Easy, no problems both before and after nozzle damage. Have to be patient with velocity tracking - want to get there sooner than flight director commands.

- HOVER: Excellent, breakout wouldn't make any difference.

AIRCRAFT RESPONSE: No problems pitch, roll. Directional not even noticed. Thrust control good, although display discrepancy between where we really were and what the digital readout said. Velocity control no problem. Turbulence not a factor.

DISPLAY CHARACTERISTICS: No problems. In hover, scan is noticeable because flight director is at top and status action is at bottom.

SUMMARY: Hover would make no difference. Wind conditions ideal.

CONTROL SYSTEM:	1.0 RCAH	PILOT RATING:	-/3C/3
SAS LIMITS:	AV-8B	BREAKOUT:	NO
CONTROL SENS.:	.23/.62	FLIGHT NO.:	F-178
DISPLAY:	ED2-0		

GENERAL: Some extra work in pitch at last part of transition, not a big problem.

APPROACH PERFORMANCE:

- INTERCEPT: Satisfactory. Velocity command diamond doesn't seem to respond at quite the right rate for closing on the localizer.

- TRACKING: Good both before and after nozzle change. Velocity tracking no real concern - had to pay attention to pitch attitude and make sure I cross-checked.

- HOVER: Could stabilize position adequately. Height discrepancy on display I'm ignoring. Breakout wouldn't make difference.

AIRCRAFT RESPONSE: No complaints pitch and roll - would like a little more sensitivity to handle middle part of transition. Directional not a factor. No real height control problem. Some work required for velocity tracking, but satisfactory. Turbulence noticeable but not a problem.

DISPLAY CHARACTERISTICS: No complaints.

SUMMARY: Controllable, adequate performance, overall satisfactory, mildly unpleasant deficiency is pitch response in transition. Same without hover.

CONTROL SYSTEM:	AVSAS	PILOT RATING:	5/5C/-
SAS LIMITS:	AV-8B	BREAKOUT:	YES (100 ft AGL)
CONTROL SENS.:	.23/.50	FLIGHT NO.:	F-178
DISPLAY:	AV8-0		

GENERAL: Didn't feel at home with flight director on this display, pitch response noticeably sensitive, flight director seems to jump around.

APPROACH PERFORMANCE:

- INTERCEPT: Could get job done. Flight director jittery, takes time to get two hands working with this director.

- TRACKING: After nozzle change vertical director just took off, sensitivity seems too high. Lateral seemed low on sensitivity.

- HOVER: Broke out at 30 kt, so getting to hover was no problem. Breakout likely did help because don't know where I am with this display.

AIRCRAFT RESPONSE: No complaints pitch and roll. Directional had some problems with getting ball out, difficult to correct. Thrust difficult to follow director. Velocity tracking hard because of display format, have to hold pitch attitude independently, get mixed up occasionally and follow director with longitudinal stick. Turbulence noticeable but not really factor.

DISPLAY CHARACTERISTICS: That's where airplane falls down, as have discussed.

SUMMARY: Adequate, but could not achieve desired performance.

CONTROL SYSTEM:	AVSAS	PILOT RATING:	-/5½C/4½
SAS LIMITS:	AV-8B	BREAKOUT:	NO
CONTROL SENS.:	.23/.50	FLIGHT NO.:	F-178
DISPLAY:	ED2-1		

GENERAL: Confusing. Hard to tell if problems were me or airplane. Couldn't be as precise as desired, problems with airspeed control on approach, interaction between throttle and pitch attitude.

APPROACH PERFORMANCE:

- INTERCEPT: Localize ok. Some problem with glideslope because airspeed kept getting low and had to concentrate on pitch attitude.

- TRACKING: Localizer ok. Problems due to inattention, but was working at it and didn't like it before and after nozzle change. Velocity poor - I didn't seem to be connected to pitch attitude and velocity.

- HOVER: Had to spend extra time getting everything sorted out, couldn't get to where I wanted on pad in reasonable time. Breakout would therefore help.

AIRCRAFT RESPONSE: Roll ok. I seemed isolated in pitch, couldn't see anything wrong but was constantly fooling around to coordinate it with speed control. Directional no problem. Thrust seemed a problem, seemed to see coupling between pitch and thrust. Velocity control not satisfactory. Turbulence noticeable but not really problem.

DISPLAY CHARACTERISTICS: No direct complaints, just had pitch attitude and speed problem throughout. Was annoying but not something that could get out of hand.

SUMMARY: Controllable, adequate performance but not desired.

CONTROL SYSTEM:	AVSAS	PILOT RATING:	2½/2½C/2
SAS LIMITS:	AV-8B	BREAKOUT:	NO
CONTROL SENS.:	.23/.50	FLIGHT NO.:	F-179
DISPLAY:	AV8-5		

GENERAL: A bit twitchy but very responsive, easy to control. Some problem with crosswind getting into hover.

APPROACH PERFORMANCE:

- INTERCEPT: No difficulty. Don't always track velocity command diamond exactly, just use the status information.

- TRACKING: Quite reasonable. Have to pay attention to pitch attitude, chevron helps. Some directional problems midway through transition, got the ball out, have to change heading to contend with crosswind. Velocity tracking super after get heading cranked around.

- HOVER: No problem stabilizing. Breakout wouldn't make difference.

AIRCRAFT RESPONSE: No complaints in roll. Pitch a little jumpy but predictability not quite optimum. Directional problems settling into hover as I've said. Thrust control no problem. Velocity control good. Turbulence noticeable at altitude but not a factor on approach.

DISPLAY CHARACTERISTICS: No problems.

SUMMARY: The half is due to slight crosswind or whatever I got into at end that required rudder inputs to get things straightened around. Would improve by 1/2 if excluded that part.

CONTROL SYSTEM:	1.5 ACAH	PILOT RATING:	-/3C/
SAS LIMITS:	AV-8B	BREAKOUT:	YES (100 ft AGL)
CONTROL SENS.:	.23/1.38	FLIGHT NO.:	F-179
DISPLAY:	AV8-0		

GENERAL: Very stable, generally satisfactory, roll a little heavy for large turns and a little twitchy in hover.

APPROACH PERFORMANCE:

- INTERCEPT: No problem - lots of time with airplane control characteristics to concentrate on flight director.

- TRACKING: No problem before nozzles. After, some vertical excursion of flight director but I could concentrate on it since airplane was so stable.

- HOVER: Broke out at 30 kt, no problems.

AIRCRAFT RESPONSE: Good in pitch, a little heavy in roll. Directional no problem. thrust no difficulties - could give it lots of attention. Velocity good - could hold attitude nicely. Turbulence felt but didn't have to counteract.

DISPLAY CHARACTERISTICS: Didn't mind strange use of hands on flight director because could devote attention to it.

SUMMARY: Satisfactory. Don't think it would be much different even with instrument hover.

CONTROL SYSTEM:	AVSAS	PILOT RATING:	-/6C/4½
SAS LIMITS:	AV-8B	BREAKOUT:	NO
CONTROL SENS.:	.23/.50	FLIGHT NO.:	F-179
DISPLAY:	AV8-6		

GENERAL: Don't like flight director, not happy, have no faith in it, don't like it compared to the one I've seen before [ED2-2 on F-178].

APPROACH PERFORMANCE:

- INTERCEPT: Performance only adequate.

- TRACKING: Performance only adequate. Didn't want to push nose down as commanded by flight director after nozzle change. Had concerns about velocity tracking because of flight director.

- HOVER: Could get there and stabilize airplane. Breakout not much help if just for hover - could control airplane, just didn't like display.

AIRCRAFT RESPONSE: Attitude responses satisfactory. Directional ok with some tendency to lose heading and get ball out. Velocity control a concern if I tried to follow flight director. Turbulence noticed but not a factor.

DISPLAY CHARACTERISTICS: Other than problems I have discussed with pitch director, also didn't seem connected to throttle director, seemed slippery, couldn't see effects of inputs.

SUMMARY: Could do job and workload was tolerable. Very objectionable deficiencies, mostly due to display. Might give it a 4-1/2 if could breakout before whole transition.

CONTROL SYSTEM:	1.5 ACAH	PILOT RATING:	4/4C/4
SAS LIMITS:	AV-8B	BREAKOUT:	No
CONTROL SENS.:	.23/1.38	FLIGHT NO.:	F-179
DISPLAY:	AV8-3		

GENERAL: I seem to do a lot better job than with previous one [AVSAS/AV8-6, F-179] on flight director and that bothers me quite a bit. Some quiver in director but a lot more believable. Still don't really like throttle director.

APPROACH PERFORMANCE:

- INTERCEPT: No difficulty, kept errors small so I could fly it precisely.

- TRACKING: Followed reasonably accurately both before and after nozzle change, never saw large errors like last configuration, could keep them small. No real concerns about velocity tracking.

- HOVER: Could get there, flight director led me to zero on the mileage so even though didn't have situation display it was comfortable. Don't think breakout would make a whole lot of difference.

AIRCRAFT RESPONSE: Attitudes good, no tendency to overcontrol, sensitivities satisfactory. Directional not a problem -- kept heading under control. Thrust unsatisfactory -- director should help more. Velocity control satisfactory. Turbulence not factor.

DISPLAY CHARACTERISTICS: Have described problems with throttle director.

SUMMARY: Only unsatisfactory because of height director and quivering in flight director. [No rating for no hover given. Comments indicate no change.]

CONTROL SYSTEM:	1.0 ACAH	PILOT RATING:	-/2½C/1½*
SAS LIMITS:	AV-8B	BREAKOUT:	No
CONTROL SENS.:	.23/1.38	FLIGHT NO.:	F-180
DISPLAY:	ED2-2		

*Only one approach used to give rating.

GENERAL: Pitch sensitivity a bit low, had to use lots of stick to stop in hover, minor complaint.

APPROACH PERFORMANCE:

- INTERCEPT: Easy, could fly flight director very precisely.

- TRACKING: No problem before or after nozzle change. No concern for velocity tracking.

- HOVER: No problem getting stabilized. Stick motion in cockpit noticeable, continuously had to pull back, felt I had to pitch aircraft extremely nose-high. Breakout might help that part.

AIRCRAFT RESPONSE: No roll complaints. Pitch sensitivity low. No directional problems -- ideal wind conditions. Thrust no problem -- lots of time to contend with it. Velocity satisfactory. Turbulence noticeable, little burble on airplane, didn't have to do work as result.

DISPLAY CHARACTERISTICS: Would like flight director down closer to where action is.

SUMMARY: Satisfactory without improvement. Want to downgrade for the pitch sensitivity. If removed hover, would be 1-1/2. I think one approach is all you need on this one to see the problems, is valid rating.

CONTROL SYSTEM:	AVSAS	PILOT RATING:	5/5C/5
SAS LIMITS:	AV-8B	BREAKOUT:	NO
CONTROL SENS.:	.23/.50	FLIGHT NO.:	F-181
DISPLAY:	ED2-2		

GENERAL: Controllable, could do job, but not really satisfactory, really can't understand why.

APPROACH PERFORMANCE:

- INTERCEPT: Localizer no problem. Had trouble with glideslope getting organized between throttle and pitch, got large airspeed errors.

- TRACKING: Had trouble with airspeed before nozzle change, wasn't too bad after. Seemed to really notice attitude changes. Could follow director, but commands seemed large and it didn't seem to feed me accurately to center of pad.

- HOVER: No overshoot or stabilization problems. Brakout wouldn't make any difference.

AIRCRAFT RESPONSE: Pitch, roll no problems. Directional some weird wind conditions but no real complaints. Thrust control seemed to have some coupling. Velocity control unsatisfactory. Turbulence not a factor.

DISPLAY CHARACTERISTICS: Would like directors lower down. Sensitivity of director seemed not good enough in hover.

SUMMARY: Have to work harder than I want. Didn't achieve desired performance but compensation was only moderate. Removing hover wouldn't change it.

CONTROL SYSTEM:	AVSAS	PILOT RATING:	-/4½D/4½
SAS LIMITS:	AV-8B	BREAKOUT:	NO
CONTROL SENS.:	.23/.50	FLIGHT NO.:	F-181
DISPLAY:	AV8-5		

GENERAL: Have to hold big nose high attitudes to station ourselves in hover because of wind, adding measurably to work load.

APPROACH PERFORMANCE:

- INTERCEPT: Localizer no problem. Glide slope had troubles correlating pitch stick with throttle, would concentrate on airspeed and glide slope would deteriorate.

- TRACKING: Localizer not a problem. Had to concentrate on glide slope more than desired, things happening faster, we have a tailwind, could do velocity tracking reasonably well if got the nose up early.

- HOVER: Overshot on first approach, anticipated nose-up requirement on second so could stabilize. Breakout wouldn't make much difference.

AIRCRAFT RESPONSE: Didn't seem to be able to stabilize pitch attitude the way I would like to, deteriorated my performance. No roll complaints. Directional nothing noticed. Thrust workload seemed to couple with pitch attitude. Longitudinal velocity control therefore not satisfactory. Wind a factor in work-load.

DISPLAY CHARACTERISTICS: Some problems getting right airspeed initially.

SUMMARY: Somewhere between desired and adequate performance achieved. [No rating for no hover - comments indicate no change].

CONTROL SYSTEM:	1.0 ACAH	PILOT RATING:	6/6D/6
SAS LIMITS:	AV-8B	BREAKOUT:	No
CONTROL SENS.:	.23/1.38	FLIGHT NO.:	F-181
DISPLAY:	ED2-1		

GENERAL: Roll overly sensitive, tendency to oscillate in roll on approach.

APPROACH PERFORMANCE:

- INTERCEPT: Strange lateral-directional characteristics, overly sensitive, kept anticipating problems that I didn't really have but was high workload. Distracted from ability to pay attention to glideslope.

- TRACKING: Same problems before nozzle change. Better after, but roll sensitivity still high. Some difficulty with velocity tracking.

- HOVER: Overrode simulation on second approach by putting ducts manually all the way to 90° to get more reasonable attitudes in hover, could get stabilized. Breakout wouldn't help.

AIRCRAFT RESPONSE: Pitch sensitive, roll very sensitive, some funny directional movements. I couldn't coordinate. Velocity control ok after nozzles, but unsatisfactory before.

DISPLAY CHARACTERISTICS: No difficulties.

SUMMARY: Adequate performance but extensive compensation. (No rating for no hover: comments indicate no change).

CONTROL SYSTEM:	AVSAS	PILOT RATING:	6/7D/6
SAS LIMITS:	AV-8B	BREAKOUT:	NO
CONTROL SENS.:	.23/.50	FLIGHT NO.:	F-181
DISPLAY:	ED2-0		

GENERAL: Airplane poor directionally, airplane didn't seem very stable in pitch on approach. Major problems on initial part of approach.

APPROACH PERFORMANCE:

- INTERCEPT: Localizer difficult, weird coordination required. Glide slope high workload, pitch seemed to have mind of its own.

- TRACKING: Unsatisfactory before nozzles because of pitch and variations in airspeed. Better after, didn't have coordination difficulties in velocity tracking, was adequate.

- HOVER: Difficult, wind is fighting me. Couldn't do good job. Breakout would help, although wouldn't cure all the problems.

AIRCRAFT RESPONSE: Roll no problem. Pitch difficult to stabilize. Directional a problem early in approach, not in hover. Didn't have time to watch thrust control. Wind or airplane screwed up hover.

DISPLAY CHARACTERISTICS: No comments

SUMMARY: Could not do job in hover adequately. Could do it if remove hover but don't like it.

CONTROL SYSTEM:	2.0 ACAH	PILOT RATING:	7½/7½D/7*
SAS LIMITS:	AV-8B	BREAKOUT:	NO
CONTROL SENS.:	.33/1.38	FLIGHT NO.:	F-181
DISPLAY:	AV8-5		

*Rating based on only one approach.

GENERAL: Easy to overcontrol both pitch and roll, get feeling aircraft might get away if make correction roughly. Hover confusing with that display and the weird wind.

APPROACH PERFORMANCE:

- INTERCEPT: Localizer possible. Was distracted by tendency to overcontrol on guidepath, but could recover it after large initial offset.

- TRACKING: Before nozzles tendency to overcontrol pitch and to some extent roll. After change, reasonable at first, but overcontrolled markedly in pitch at last part of transition.

- HOVER: Difficult to stabilize, got screwed up with display trying to get back to pad, kept rotating into wind. In today's environment, breakout would help. Major problem is associated with aircraft response throughout task, however.

AIRCRAFT RESPONSE: Pitch initial response too quick, predictability poor, tend to oscillate 2 or 3 times in trying to make corrections. In hover, felt I was getting more than I asked for, feeling of taking off in attitude. Some twitchiness in roll. No directional complaints. Thrust control got lost in the action. Velocity control not satisfactory. Winds compounded hover task.

DISPLAY CHARACTERISTICS: Had interpretation problems in hover. Maybe was pushing rudder subconsciously, screwed up heading.

SUMMARY: Did not achieve adequate performance, do not like airplane. Did not think I was about to lose control, but was overcontrolling, will interpret that between 7 and 8, might go to 7 if removed hover.

APPENDIX III
IDENTIFICATION OF AIRCRAFT CHARACTERISTICS

The conduct of flying qualities experiments using response-feedback variable stability aircraft is strongly dependent on the capability to estimate dynamic characteristics from flight data. For this experiment, it was necessary to estimate the basic X-22A characteristics, in hover and forward flight, in order to compute the variable stability gains necessary to change the characteristics to those of the AV-8B. In addition, it was desired to identify the simulated characteristics with the VSS operating in order to validate the resulting simulation. The results for the former type follow those of previous X-22A programs, and are summarized below. Attempting to identify the simulated results, however, proved to be very difficult, primarily because of the unstable basic AV-8B characteristics that were being simulated. A new approach to the identification was devised and is outlined here, with a very preliminary result that demonstrates reasonable simulation validity in the hover. Further work on the calibration data is, however, required.

BASIC X-22A CHARACTERISTICS

The identification method used to determine the basic X-22A characteristics was the locally iterated Kalman filter technique developed by Calspan for the X-22A. The development of this technique is given in Reference 31, and a summary of its application in previous X-22A flight programs is contained in References 32 and 33.

As in the previous X-22A experiment (Reference 2) the assumed equations of motion are:

Longitudinal:

$$\dot{u} + wq + g\sin\theta = X_0 + X_u(u-u_0) + X_w(w-w_0) + X_\theta(\theta-\theta_0) + X_{\delta_{es}}(\delta_{es} - \delta_{es_0}) + X_{\delta_c}(\delta_c - \delta_{c_0})$$

$$\dot{w} - uq - g\cos\theta = Z_0 + Z_u(u-u_0) + Z_w(w-w_0) + Z_\theta(\theta-\theta_0) + Z_{\delta_{es}}(\delta_{es} - \delta_{es_0}) + Z_{\delta_c}(\delta_c - \delta_{c_0})$$

$$\dot{q} = M_0 + M_u(u-u_0) + M_w(w-w_0) + M_q q + M_\theta(\theta-\theta_0) + M_{\delta_{es}}(\delta_{es} - \delta_{es_0}) + M_{\delta_c}(\delta_c - \delta_{c_0})$$

Lateral-Directional:

$$\dot{v} - wp + ur - g\sin\phi = Y_0 + Y_v(v-v_0) + Y_p p + Y_r r$$

$$\dot{p} = L'_0 + L'_v(v-v_0) + L'_p p + L'_\phi \phi + \left(L'_r + K_L \frac{q}{57.3}\right) r + L_{\delta_{as}}(\delta_{as} - \delta_{as_0}) + L_{\delta_{rp}}(\delta_{rp} - \delta_{rp_0})$$

$$\dot{r} = N'_0 + N'_v(v-v_0) + \left(N'_p + K_N \frac{q}{57.3}\right) p + N'_\phi \phi + N'_r r + N_{\delta_{as}}(\delta_{as} - \delta_{as_0}) + N_{\delta_{rp}}(\delta_{rp} - \delta_{rp_0})$$

$$\dot{\phi} = p + \frac{\theta q}{57.3}\sin\phi + \frac{\theta r}{57.3}\cos\phi$$

Implicit in these equations are the following assumptions:

- Longitudinal and lateral-directional motions may be considered essentially decoupled
- Calibration records are obtained in trimmed, steady flight ($q_0 = r_0 = p_0 = \phi_0 \triangleq 0$) .
- Roll and yaw control inputs contribute a negligible amount to the side force equation ($Y_{\delta_{as}} = Y_{\delta_{rp}} \triangleq 0$) .
- Attitude derivatives (e.g. M_θ, L_ϕ) are included to permit identification of records in which angular attitude augmentation was used.

Figures III-1 through III-4 present the identified results of the X-22A characteristics at hover and at 65 Kt with simple feedback loops closed. The feedback and gearing gains used in these flight records were:

	Δ_{ES}/q (in/rad/sec	Δ_{ES}/θ (in/rad)	Δ_{ES}/δ_{ES} (in/in)	Δ_{CS}/δ_{CS} (deg/deg)
V = 65 Kt	-3.97	-12.03	1.05	1.25
V = 0 Kt	-3.97	-12.03	1.05	1.25

(Longitudinal)

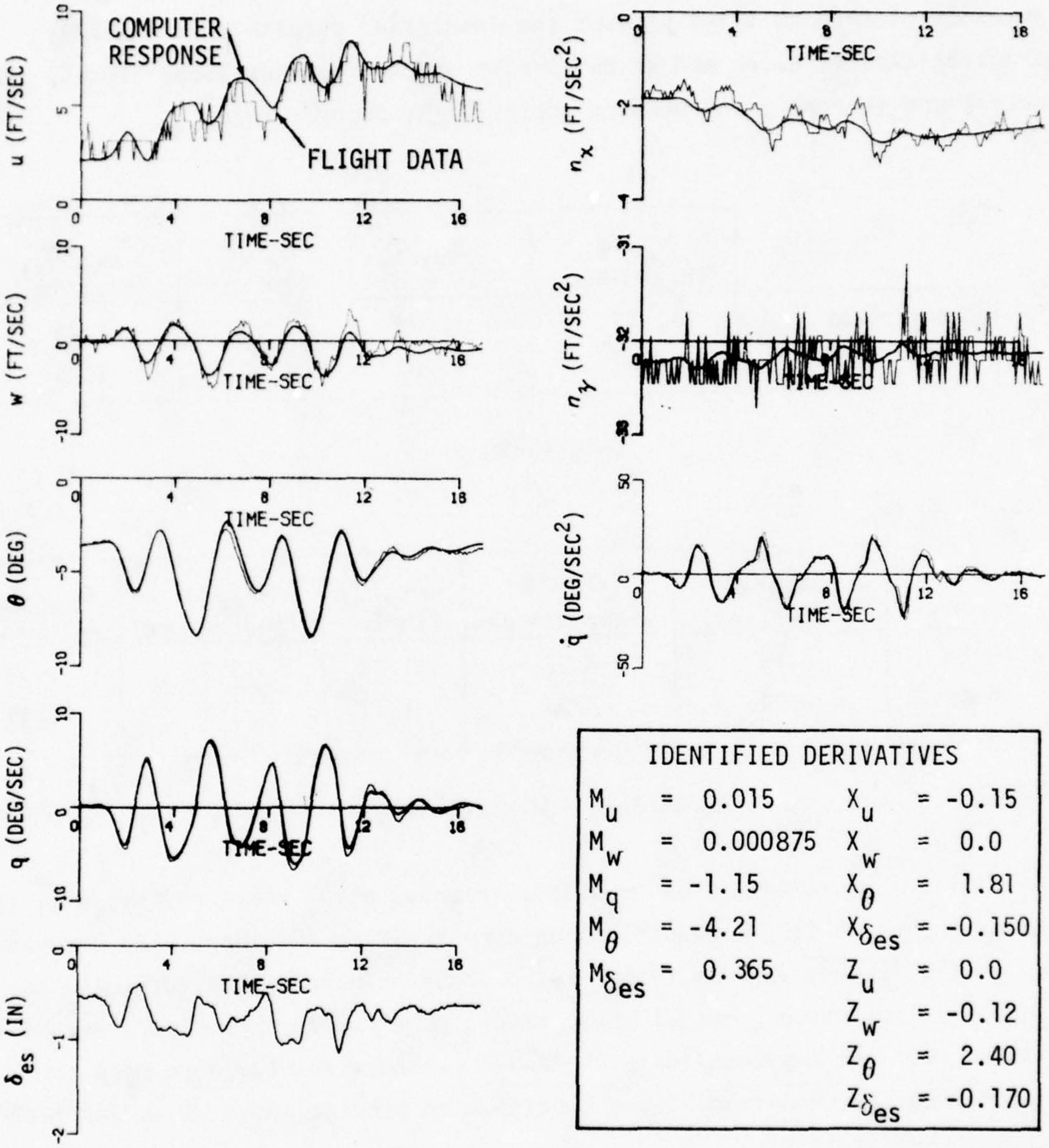
	Δ_{as}/p (in/rad/sec)	Δ_{as}/ϕ (in/rad/sec)	Δ_{as}/δ_{as} (in/in)	Δ_{rp}/r (in/rad/sec)	Δ_{RP}/δ_{RP} (in/in)
V = 65 Kt	-3.72	-7.33	1.42	-3.2	2.11
V = 0 Kt	-3.72	-7.33	1.42	-3.2	2.11

(Lateral - Directional)

Table III-1 summarizes the basic stability and control characteristics of the X-22A at these two flight conditions as computed from the identified derivatives given on the figures and the gains listed above. These values were used to compute the simulation gains at these flight conditions; approximate values for 30 Kt that are implemented in the X-22A ground simulator were used for this intermediate, non-trim flight condition to provide appropriate function generator characteristics.

SIMULATED CHARACTERISTICS

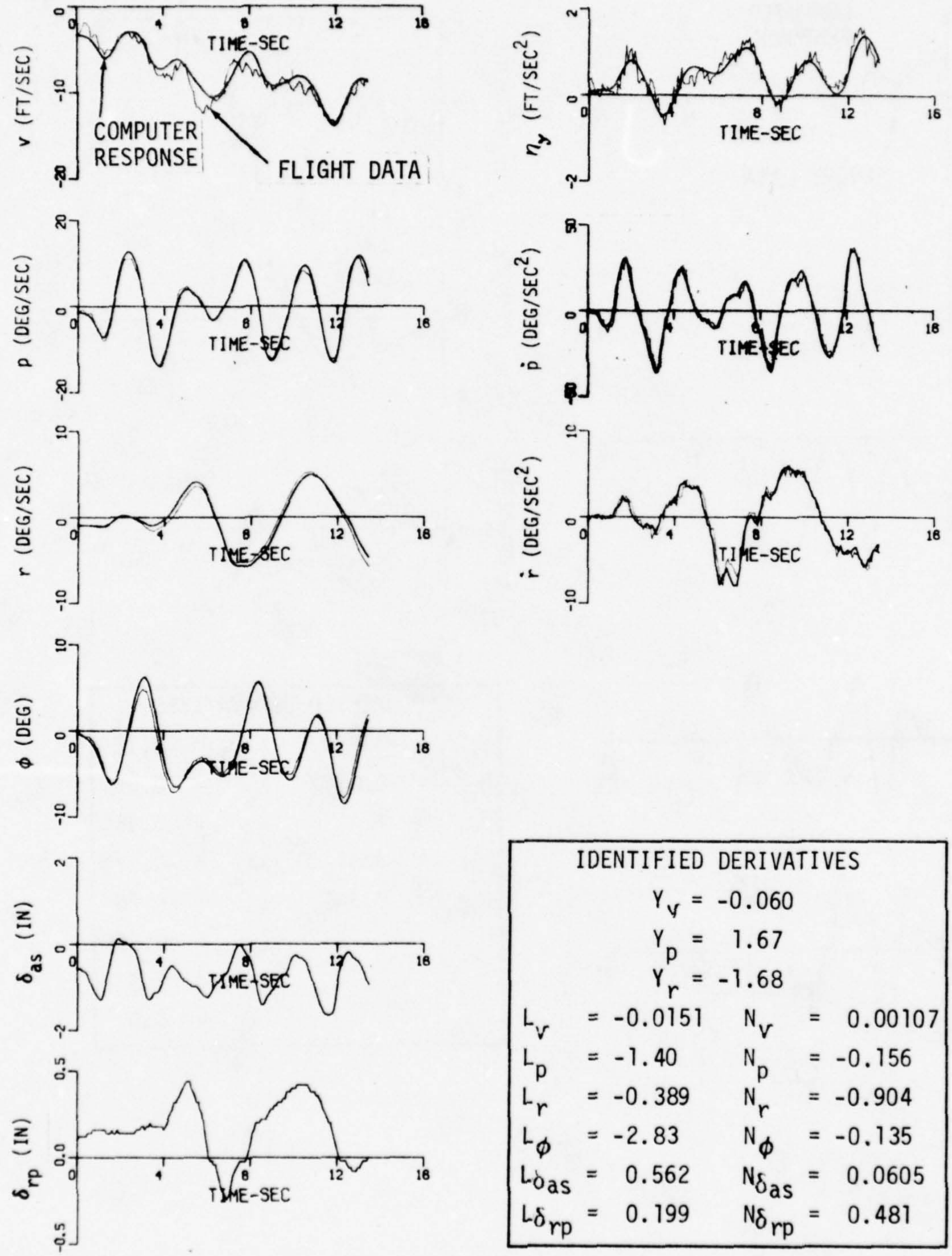
In an attempt to assure that the simulated characteristics would not be masked with augmentation gains, the calibration records of the simulated AV-8B were taken with no augmentation gains (e.g. pitch attitude)



IDENTIFIED DERIVATIVES

M_u	= 0.015	X_u	= -0.15
M_w	= 0.000875	X_w	= 0.0
M_q	= -1.15	X_θ	= 1.81
M_θ	= -4.21	$X_{\delta_{es}}$	= -0.150
$M_{\delta_{es}}$	= 0.365	Z_u	= 0.0
		Z_w	= -0.12
		Z_θ	= 2.40
		$Z_{\delta_{es}}$	= -0.170

Figure III-1 IDENTIFICATION OF LONGITUDINAL CHARACTERISTICS, 90°/0 KT



IDENTIFIED DERIVATIVES

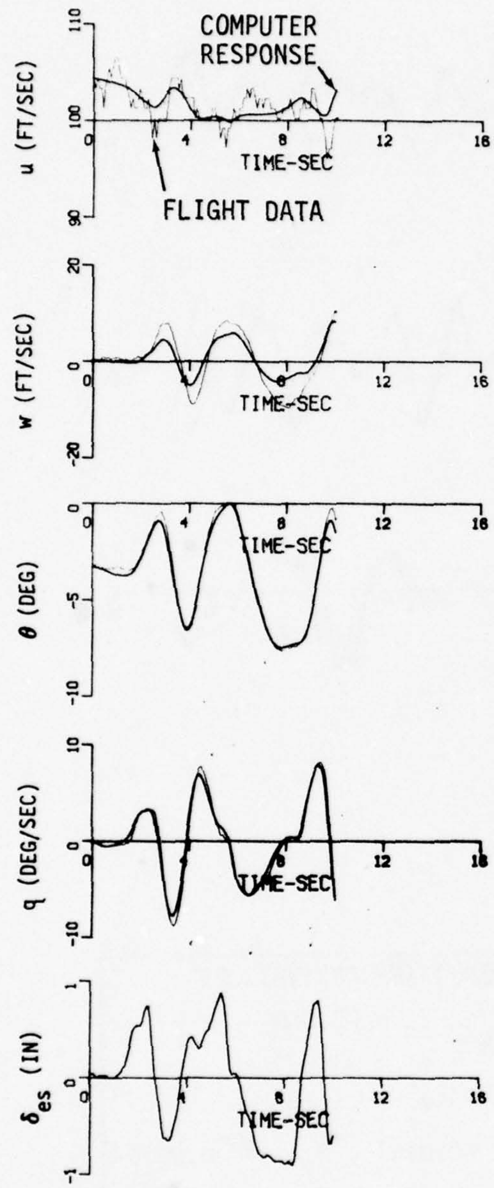
$Y_v = -0.060$

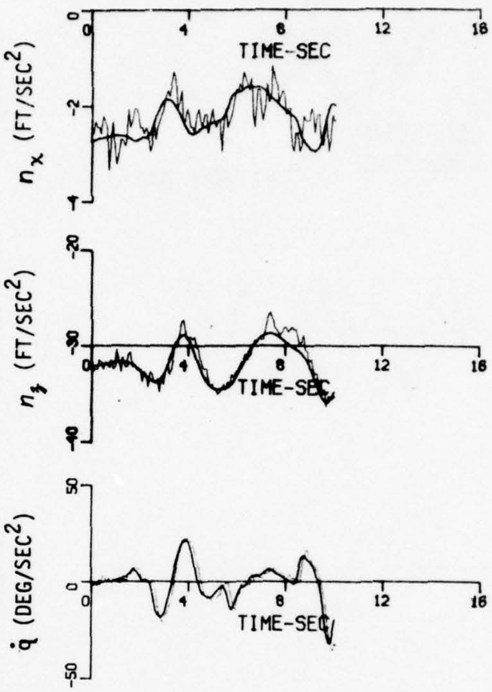
$Y_p = 1.67$

$Y_r = -1.68$

L_v	= -0.0151	N_v	= 0.00107
L_p	= -1.40	N_p	= -0.156
L_r	= -0.389	N_r	= -0.904
L_ϕ	= -2.83	N_ϕ	= -0.135
$L_{\delta_{as}}$	= 0.562	$N_{\delta_{as}}$	= 0.0605
$L_{\delta_{rp}}$	= 0.199	$N_{\delta_{rp}}$	= 0.481

Figure III-2 IDENTIFICATION OF LATERAL-DIRECTIONAL CHARACTERISTICS, 90°/0 KT

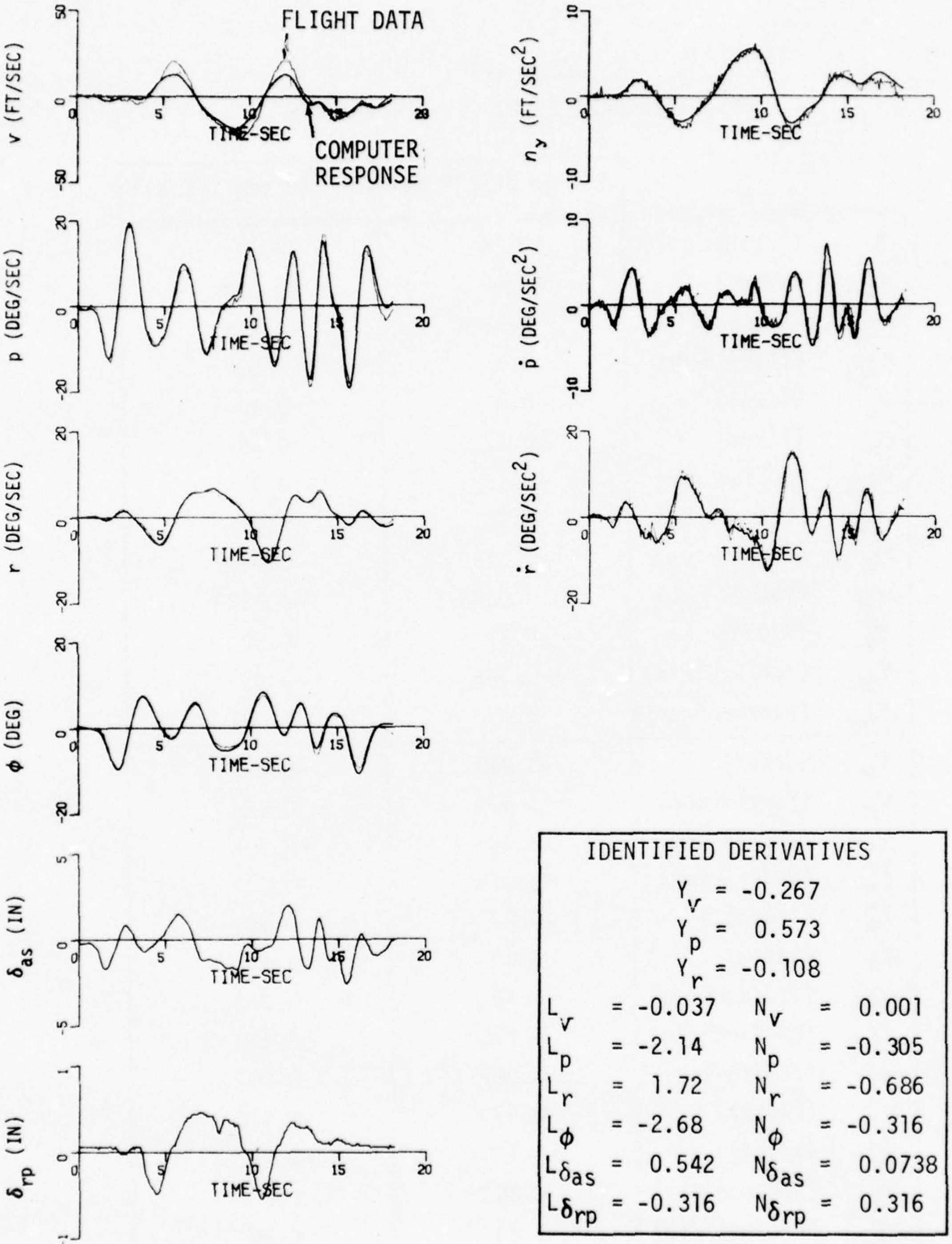




IDENTIFIED DERIVATIVES

M_u	= -0.010	X_u	= -0.18
M_w	= -0.0177	X_w	= -0.03
M_q	= -1.4	X_θ	= 4.96
M_θ	= -4.35	$X_{\delta_{es}}$	= -0.374
$M_{\delta_{es}}$	= 0.346	Z_u	= -0.20
		Z_w	= -0.55
		Z_θ	= 0.0
		$Z_{\delta_{es}}$	= 0.0

Figure III-3 IDENTIFICATION OF LONGITUDINAL CHARACTERISTICS, 50°/65 KT



IDENTIFIED DERIVATIVES

Y_v = -0.267

Y_p = 0.573

Y_r = -0.108

L_v	= -0.037	N_v	= 0.001
L_p	= -2.14	N_p	= -0.305
L_r	= 1.72	N_r	= -0.686
L_ϕ	= -2.68	N_ϕ	= -0.316
$L_{\delta as}$	= 0.542	$N_{\delta as}$	= 0.0738
$L_{\delta rp}$	= -0.316	$N_{\delta rp}$	= 0.316

Figure III-4 IDENTIFICATION OF LATERAL-DIRECTIONAL CHARACTERISTICS, 50°/65 KT

TABLE III-1

BASIC AIRCRAFT STABILITY DERIVATIVES

		λ = 90 deg (0 Kt)	λ = 50 deg (65 Kt)
X_u	(1/sec)	-0.15	-0.18
X_w	(1/sec)	0.0	-0.030
$X_{\delta_{es}}$	(ft/sec^2/in)	-0.143	-0.356
$X_{\delta_{cs}}$	(ft/sec^2/deg)	0.0	0.52
Z_u	(1/sec)	0.0	-0.20
Z_w	(1/sec)	-0.12	-0.55
$Z_{\delta_{es}}$	(ft/sec^2/in)	-0.16	0.0
$Z_{\delta_{cs}}$	(ft/sec^2/deg)	-1.50	-1.00
M_u	(rad/ft-sec)	0.015	-0.010
M_w	(rad/ft-sec)	0.000875	-0.0177
M_q	(1/sec)	0.23	-0.09
$M_{\delta_{es}}$	(rad/sec^2/in)	0.348	0.33
$M_{\delta_{cs}}$	(rad/sec^2/deg)	0.0	0.021
Y_v	(1/sec)	-0.060	-0.267
Y_p	(ft/rad-sec)	1.67	0.573
Y_r	(ft/rad-sec)	-1.68	-0.108
L'_v	(rad/ft-sec)	-0.015	-0.037
L'_p	(1/sec)	+0.07	-0.75
L'_r	(1/sec)	0.0	1.24
$L'_{\delta_{as}}$	(rad/sec^2/in)	0.40	0.382
$L'_{\delta_{rp}}$	(rad/sec^2/in)	0.095	-0.150
N'_v	(rad/ft-sec)	0.0011	0.001
N'_p	(1/sec)	0.0	-0.110
N'_r	(1/sec)	-0.17	-0.21
$N'_{\delta_{as}}$	(rad/sec^2/in)	0.043	0.052
$N'_{\delta_{rp}}$	(rad/sec^2/in)	0.23	0.15

functioning. In retrospect, this decision was a mistake. The difficulty lies in the fact that the longitudinal characteristics of the AV-8B model used for the simulation are statically unstable (positive real root) at both hover and 65 Kt. This characteristic makes digital identification using the equations listed earlier extremely difficult to perform; it also makes conventional maximum-likelihood techniques exhibit convergence problems. As a result, time history matches of the quality shown in Figures III-1 through III-4 could not be obtained, even using the computed simulation characteristics as "valid" initial estimates.

There are essentially two difficulties with the identification procedures used for the basic (augmented) X-22A characteristics when an unstable system is to be identified, both of which involve ascertaining the predominant unstable root accurately. First, it is combinations of the stability derivatives (e.g. $Z_u M_w - Z_w M_u$) that determine the extent of the instability; hence small errors in any of the derivatives lead to large differences in the unstable characteristics (e.g. time to double amplitude). For these situations, if the system can be considered linear, a preferable approach would be to recast the equations of motion in a form that more nearly depends on the transfer function characteristics. This modification is outlined below. Even in this form, however, the very fact that the system has an unstable root frequency leads to convergence problems. A method for shifting the problem to a stable situation for the identification, which is particularly amenable to the recast equations, has also been developed and applied successfully to flight data. Both of these procedures are outlined below; a more complete description is given in Reference 34.

If the airplane exhibits characteristics that are reasonably linear, the equations of motion are written:

$$\dot{x} = Fx + Gu$$

$$y = Hx$$

The elements of F are the stability derivatives, in G are the control derivatives, and H relates the measurements to the states. Since the equations

are linear, one can define any new state $x = TZ$ by an appropriate transformation T. When there is one controller, a particularly useful transformation matrix is composed of the elements of the numerator polynomials of the transfer functions $y(s)/u_s$. This transformation is the phase variable canonical transformation; assuming that H is known, and picking H = I (identify matrix), the equations become:

$$\dot{z} = F_o Z + G_o u_s$$

$$y = TZ$$

For a three degree of freedom airplane problem (fourth order equations), we have:

$$F_o = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -a_o & -a_1 & -a_2 & -a_3 \end{bmatrix}, \quad G_o = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}, \quad T = 4 \times 4$$

What is particularly useful for identification purposes is the fact that the a_i are the coefficients of the characteristic polynomial (e.g. $\Delta(s) = s^4 + a_3 s^3 + a_2 s^2 + a_1 s + a_o$); hence, the parameters being identified directly influence the roots.

For systems with an unstable real root, however, even using the phase canonical form can lead to numerical convergence problems. In Section 3 of this report, a procedure was outlined in which control system computations were made after shifting a problem with an unstable root to the left-hand plane by an arbitrary amount. In the time domain, this frequency-domain shift is equivalent to a multiplication by $e^{-\lambda t}$, where λ is the amount of the shift. Hence, for identification purposes, one can consider writing the state equations in the shifted domain and multiplying the data by $e^{-\lambda t}$. For the example of the phase variable equations given above, the shifted F_o becomes:

$$\hat{F}_o = \begin{bmatrix} -\lambda & 1 & 0 & 0 \\ 0 & -\lambda & 1 & 0 \\ 0 & 0 & -\lambda & 1 \\ -a_o & -a_1 & -a_2 & (-a_3 - \lambda) \end{bmatrix}$$

Although the concept of writing the equations in the phase variable form was not developed specifically for this X-22A program, the additional concept of the shift was, albeit somewhat late. As a result, insufficient time to "tune" the procedures for the X-22A data was available prior to publication of this report. A preliminary result, however, is given in Figure III-5. The identified T and F_o matrices are; after removing the shift ($\lambda = 1.0$ in this case):

$$T = \begin{bmatrix} -.39 & -7.06 & .78 & 1.17 \\ 0 & .85 & 4.73 & 15.34 \\ .85 & 4.73 & 15.34 & 0 \\ 2.33 & 2.71 & 6.39 & -.29 \end{bmatrix}$$

$$F_o = \begin{bmatrix} 0 & 1.0 & 0 & 0 \\ 0 & 0 & 1.0 & 0 \\ 0 & 0 & 0 & 1.0 \\ .029 & .115 & .230 & .107 \end{bmatrix}$$

The stability and control derivatives are now found by performing the inverse transformations:

$$F = TF_oT^{-1}, \quad G = TG_o$$

The resulting stability and control derivatives of the simulation are given below:

$X_u = -.25$ $\quad M_u = -.0014$ $\quad X_{\delta_{ES}} = 1.17$

$X_w = +.17$ $\quad M_w = +.0025$ $\quad Z_{\delta_{ES}} = -.29$

$Z_u = -.25$ $\quad M_q = +.49$ $\quad M_{\delta_{ES}} = .26$

$Z_w = -.069$

It is emphasized that these results are preliminary. As can be seen, the time history matches are not of the quality shown in Figures III-1 through III-4, and the identified derivatives do not match exactly the computed simulation

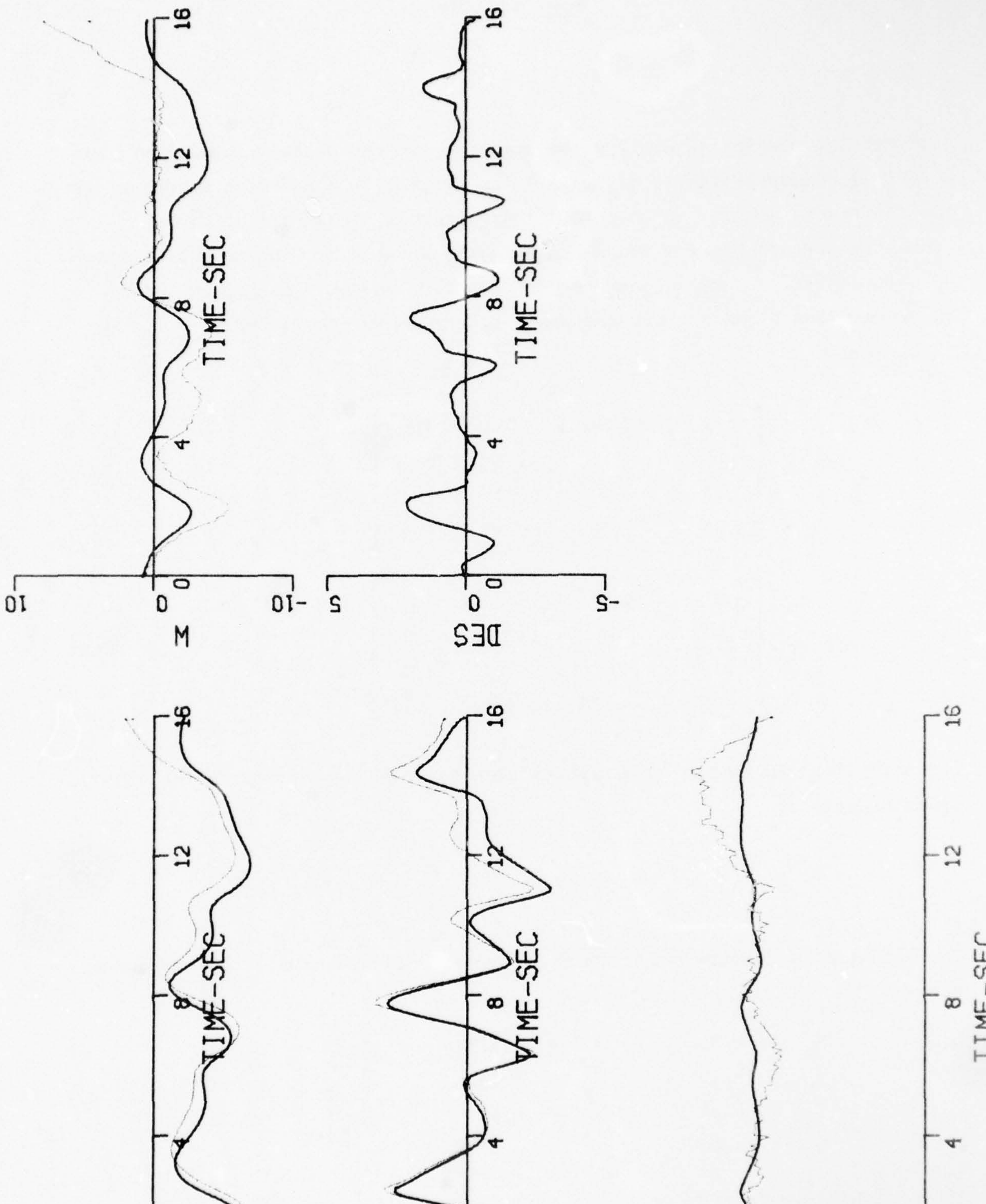


Figure III-5 PRELIMINARY RESULTS: AV-8B SIMULATION AT HOVER

derivatives discussed in Section 3 of this report. Nonetheless, the trends in the changes of the stability derivatives from the basic X-22A are generally correct, and the time histories show the correct qualitative motions. Further work is therefore recommended on the calibration data from this experiment.

APPENDIX IV
MEASURED WINDS AND TURBULENCE

Time histories of ambient airmass velocity were calculated from on-board measurements of the three body axis components of airspeed and the filtered estimates of inertial velocity. The procedure employed is described in Reference 2. The means (steady winds) and standard deviations (RMS turbulence levels) of the horizontal components of the ambient wind are summarized in Table IV-1. Because of the definition of the reference earth axis system, a positive value of crosswind designates a wind from the pilot's left during the approach.

TABLE IV-1

MEASURED WINDS AND TURBULENCE

FLT NO	APPROACH NO	CONTROL CONFIG	DISPLAY CONFIG	HEADWIND MEAN (ft/sec)	HEADWIND STD DEV (ft/sec)	CROSSWIND MEAN (ft/sec)	CROSSWIND STD DEV (ft/sec)
158	1	ACAH 1.0	ED2-0	NO DATA		NO DATA	
	2	"	"	18.8	2.9	13.6	3.4
	3	AVSAS	AV8-0	21.3	2.9	9.9	3.4
	4	"	"	20.3	2.3	13.4	2.7
	5	RCAH 2.0	AV8-5	21.1	2.2	17.0	3.6
	6	"	"	20.6	2.9	15.6	3.7
160	1	ACAH 1.5	AV8-0	NO DATA		NO DATA	
	2	"	"	-22.1	2.7	11.6	3.4
	3	RCAH 1.0	AV8-5	-20.5	2.7	8.1	3.3
	4	"	"	-20.3	1.6	8.3	2.0
162	1	AVSAS	AV8-5	25.7	3.3	-19.7	5.2
	2	"	"	33.4	6.0	-16.1	6.2
	3	ACAH 1.5	ED2-0	NO DATA		NO DATA	
	4	"	"	31.2	5.6	15.8	4.4
	5	"	"	32.3	5.2	-19.2	4.1
	6	RCAH 1.0	AV8-5	27.1	5.2	-17.2	4.5
	7	"	"	32.0	4.0	-21.0	4.2
163	1	AVSAS	AV8-5	18.3	2.9	9.6	3.0
	2	"	"	16.0	3.7	8.1	3.1
	3	"	"	15.7	3.0	5.2	3.5
	4	RCAH 1.0	AV8-5	15.4	2.3	4.1	2.4
	5	"	"	14.4	2.1	5.2	3.0
	6	ACAH 1.0	ED2-0	14.9	2.4	4.9	2.4
164	1	AVSAS	ED2-2	-10.1	2.8	-4.7	3.1
	2	"	"	-13.0	2.6	-4.1	2.7
	3	RCAH 1.0	ED2-0	-11.3	3.6	-4.2	2.9
	4	"	"	-12.2	2.6	-1.6	2.9
	5	ACAH 1.0	AV8-6	-12.1	2.7	-5.6	2.3
	6	"	"	-13.1	3.4	-6.5	3.3

TABLE IV-1 (Cont)

MEASURED WINDS AND TURBULENCE

FLT NO	APPROACH NO	CONTROL CONFIG	DISPLAY CONFIG	HEADWIND MEAN (ft/sec)	HEADWIND STD DEV (ft/sec)	CROSSWIND MEAN (ft/sec)	CROSSWIND STD DEV (ft/sec)
165	1	AVSAS	AV8-6	20.6	3.3	16.9	3.0
	2	"	"	15.5	4.0	15.1	3.8
	3	AVSAS	AV8-3	NO DATA		NO DATA	
	4	"	"	12.6	2.9	11.8	2.6
	5	ACAH 1.0	AV8-6	14.2	2.9	17.1	2.9
	6	"	"	13.7	2.9	16.1	2.5
166	1	AVSAS	AV8-6	10.5	2.0	5.9	2.7
	2	"	"	11.2	3.0	2.7	2.5
	3	AVSAS	ED2-1	7.2	2.3	4.3	2.9
	4	"	"	8.4	3.3	4.7	3.4
	5	ACAH 1.0	AV8-6	4.9	2.7	6.1	2.4
	6	"	"	5.6	2.9	6.4	3.2
167	1	AVSAS	ED2-0	15.1	2.1	6.4	3.0
	2	"	"	13.2	3.5	8.6	3.1
	3	AVSAS	AV8-0	10.9	3.2	11.1	2.2
	4	"	"	13.9	3.4	13.4	3.2
	5	"	"	13.7	2.4	10.0	2.5
	6	ACAH 1.0	AV8-5	13.8	3.1	14.4	2.6
	7	"	"	15.3	2.2	14.5	2.3
168	1	RCAH 2.0	ED2-0	16.1	2.5	6.5	1.8
	2	"	"	13.0	3.4	2.7	2.4
	3	ACAH 1.0	ED2-0	16.6	1.7	9.5	2.3
	4	"	"	16.4	2.0	10.2	1.5
	5	ACAH 2.0	ED2-0	14.1	1.8	7.5	1.7
	6	"	"	17.1	2.3	10.0	2.0
	7	RCAH 2.0	ED2-0	14.3	2.9	1.7	2.0
169	1	ACAH 2.0	ED2-0	29.9	5.3	-1.3	3.4
	2	RCAH 2.0	AV8-3	30.6	5.8	-1.6	3.8

TABLE IV-1 (Cont)

MEASURED WINDS AND TURBULENCE

FLT NO	APPROACH NO	CONTROL CONFIG	DISPLAY CONFIG	HEADWIND MEAN (ft/sec)	HEADWIND STD DEV (ft/sec)	CROSSWIND MEAN (ft/sec)	CROSSWIND STD DEV (ft/sec)
177	1	RCAH 2.0	AV8-5	-14.9	2.2	8.5	1.1
	2	"	"	-13.7	3.2	8.6	2.4
	3	AVSAS	ED2-0	-14.6	2.6	13.8	3.9
	4	"	"	-13.4	3.0	7.7	3.4
178	1	AVSAS	ED2-2	19.7	2.4	-7.3	2.4
	2	"	"	17.1	2.5	-6.9	1.9
	3	RCAH 1.0	ED2-0	16.8	2.0	-10.2	2.9
	4	"	"	16.6	4.1	-10.8	2.3
	5	AVSAS	AV8-0	12.6	3.4	-12.2	2.4
	6	"	"	16.5	3.6	-13.3	2.6
	7	AVSAS	ED2-1	14.9	3.3	-10.3	2.6
	8	"	"	18.6	2.8	-13.9	2.6
179	1	AVSAS	AV8-5	11.7	3.6	-7.6	4.0
	2	"	"	10.9	3.0	-6.6	4.4
	3	ACAH 1.5	AV8-0	7.1	2.4	-7.7	1.7
	4	"	"	11.9	2.5	-5.7	2.2
	5	AVSAS	AV8-6	9.8	2.2	-7.1	2.8
	6	"	"	14.8	4.3	-6.7	3.4
	7	ACAH 1.5	AV8-3	15.0	2.6	-4.0	2.0
	8	"	"	16.0	2.7	-5.2	2.1
180	1	ACAH 1.0	ED2-2	-2.6	4.0	.1	2.5
181	1	AVSAS	ED2-2	-11.1	3.5	-8.6	2.6
	2	"	"	-10.2	2.9	-9.9	2.7
	3	AVSAS	AV8-5	-12.4	2.7	-11.2	4.2
	4	"	"	-15.3	2.3	-10.1	3.1
	5	ACAH 1.0	ED2-1	-16.5	2.9	-8.2	3.0
	6	"	"	-17.3	2.7	-8.7	3.8
	7	AVSAS	ED2-0	-19.3	2.9	-6.0	3.4
	8	"	"	-20.8	2.0	-8.4	2.8
	9	ACAH 2.0	AV8-5	-20.2	3.5	-5.8	3.8

APPENDIX V
EXPERIMENTAL EQUIPMENT

The major elements of the experimental equipment used to conduct the experiment described in this report are:

- The X-22A VTOL Research Airplane with its Variable Stability System (VSS), variable flight control system and programmable electronic display systems, both head-up and head-down.

- The telemetry van which houses the communications, data acquisition and data processing systems.

- The Microwave Landing System (MLS) which provides approach and landing guidance.

- The X-22A Ground Simulator.

Significant features of these major elements of experimental equipment are described in this Appendix.

THE X-22A - V/STOL IN-FLIGHT SIMULATOR

Capabilities

The X-22A V/STOL Flight Research Facility represents the only Navy-owned in-flight simulation capability applicable to hover, low speed and transition flight investigation of fixed wing V/STOL flying qualities. The facility, consisting of the X-22A variable stability aircraft, fixed based ground simulator, telemetry van, and microwave landing system is currently operated by the Flight Research Branch of Calspan Corporation under the cognizance of the Flight Dynamics Branch of the Naval Air Development Center. The combination of a wide range of flight conditions, vehicle and control dynamics,

a portable MLS for guidance and a programmable Head-Up-Display (HUD) provides a significant research and development capability for investigating flying qualities, stability and control, and flight safety of existing and proposed V/STOL aircraft.

Specifically, the X-22A research facility capabilities are suited to the following general aspects of Navy V/STOL research and development:

- Simulation of generic characteristics for:

  (a) verifying ground simulator results;
  (b) flight testing control/display interfaces;
  (c) validating existing and proposed specification requirements;

- Simulation of specific configurations for:

  (a) supporting aircraft development;
  (b) addressing ad hoc dynamic problems;
  (c) flight crew training prior to first flight;
  (d) developing and validating pilot/system interfaces;
  (e) developing improved flight test techniques.

Although this list is by no means complete, it nonetheless points out the wide range of present and future V/STOL problem areas which may be addressed with this research facility.

Basic X-22A

The X-22A aircraft was developed by the Bell Aerosystems Company during a seven-year effort managed by the Naval Air Systems Command (NASC), and was designed to be a variable stability aircraft from the start with Calspan responsible for the variable stability system. In 1970, the Naval Air Systems Command awarded a contract to Calspan to begin flying qualities research with the X-22A.

As is evident from Figure V-1, the X-22A has four ducted propellers and four engines. The engines are connected to a common system of rotating shafts that distribute propulsive power to the four propellers. The direction of the thrust vector is changed by rotating the ducts, which are interconnected so that all rotate through the same angle. Thrust magnitude is determined by the collective pitch of the four propellers and this is controlled by either one of two levers, selectable in flight. One lever is similar to a conventional helicopter "collective stick" and the other lever can be moved fore and aft like a throttle (Figure V-2). Normal looking pitch, roll, and yaw controls in the cockpit provide the desired control moments by differentially positioning the appropriate control elements (propeller pitch or elevon deflection) in each duct (Figure V-3).

In hovering flight, the X-22A employs fore and aft differential blade pitch for pitching moments, left and right differential blade pitch for rolling moments, and left and right differential elevon deflection for yawing moments. In forward flight, fore and aft differential elevon deflection is used for pitching moments, left and right differential elevon deflection for rolling moments, and left and right differential blade pitch for yawing moments. A mechanical mixer directs and proportions the pilot's commands to the appropriate propellers and elevons as a function of the duct angle.

X-22A Variable Stability System (VSS)

There are four VSS controllers - thrust, pitch, roll and yaw - and three artificial feel servos for the evaluation pilot cockpit controls, each employing electrohydraulic servos. When rigged for VSS flight the left-hand flight controls are mechanically disconnected from the right-hand flight controls and connected to the set of VSS pitch, roll, and yaw feel servos. The VSS thrust servo operates the boost servo for the collective pitch system. VSS pitch, roll and yaw servos operate the right-hand flight controls, moving the same linkages that are moved manually by the right-hand pilot in normal non-VSS flight. (In fact, these same actuators serve a dual role by providing artificial feel for the primary flight control system when the VSS is not engaged.) These control motions are phased to the blades and elevons by the mechanical mixer as in normal flight.

GENERAL SPECIFICATIONS

DIMENSIONS

Length	39.57 ft	
Height	20.69 ft	
Tread	8.0 ft	
Wing	Front	Aft
Area	139 sq ft	286 sq ft
Span	22.97 ft	39.24 ft
Aspect Ratio	3.86	5.38

ENGINE RATINGS

SHP	SLS	Thrust	rpm	Min.
1250	Mil.	154	19,500	30
1050	Nor.	132	19,500	Cont.

POWER PLANT

No. & Model	(4) YT58-GE-8D
Mfr.	General Electric Co.
Type	Free Power Turbine
Reduction	
Gear Ratio	0.133
Prop Mfr.	Hamilton Standard
Prop. Dia.	84 in.
No. of Blades	3
Tail Pipe	Fixed Area

WEIGHTS

Loading	lb
Empty	11,622
Gross	15,287
Max Takeoff	18,420
Max Landing	15,287

FUEL

No. Tanks	Gal	Location
1	465	Fuselage

Fuel Grade JP-4 or JP-5

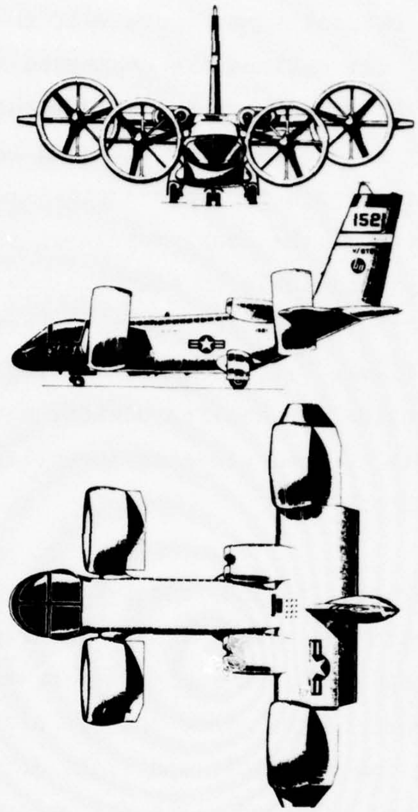


Figure V-1(a) X-22A AIRCRAFT, 3 VIEW

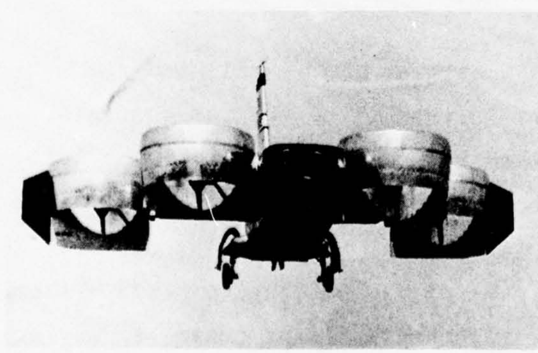


Figure V-1(b) X-22A IN HOVERING FLIGHT

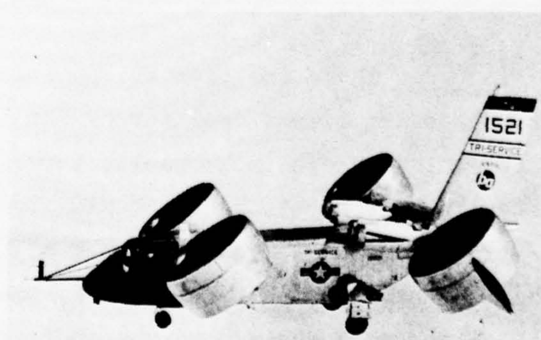


Figure V-1(c) X-22A IN FORWARD FLIGHT

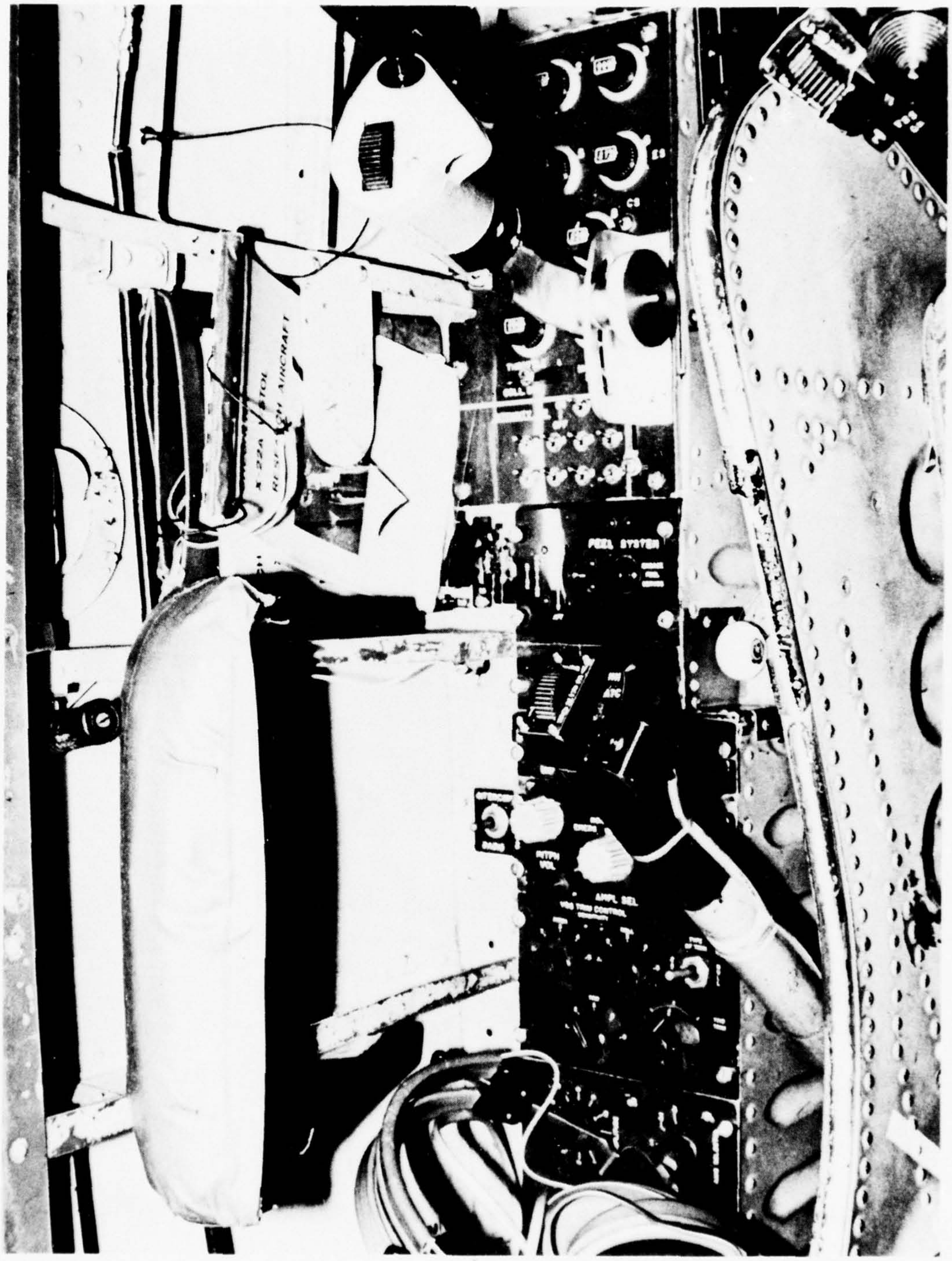


Figure V-2 EVALUATION PILOT COLLECTIVE AND THROTTLE STICKS PLUS DISPLAY SELECTION PANEL
(SIMULATED NOZZLE ANGLE CONTROLLER NOT INSTALLED)

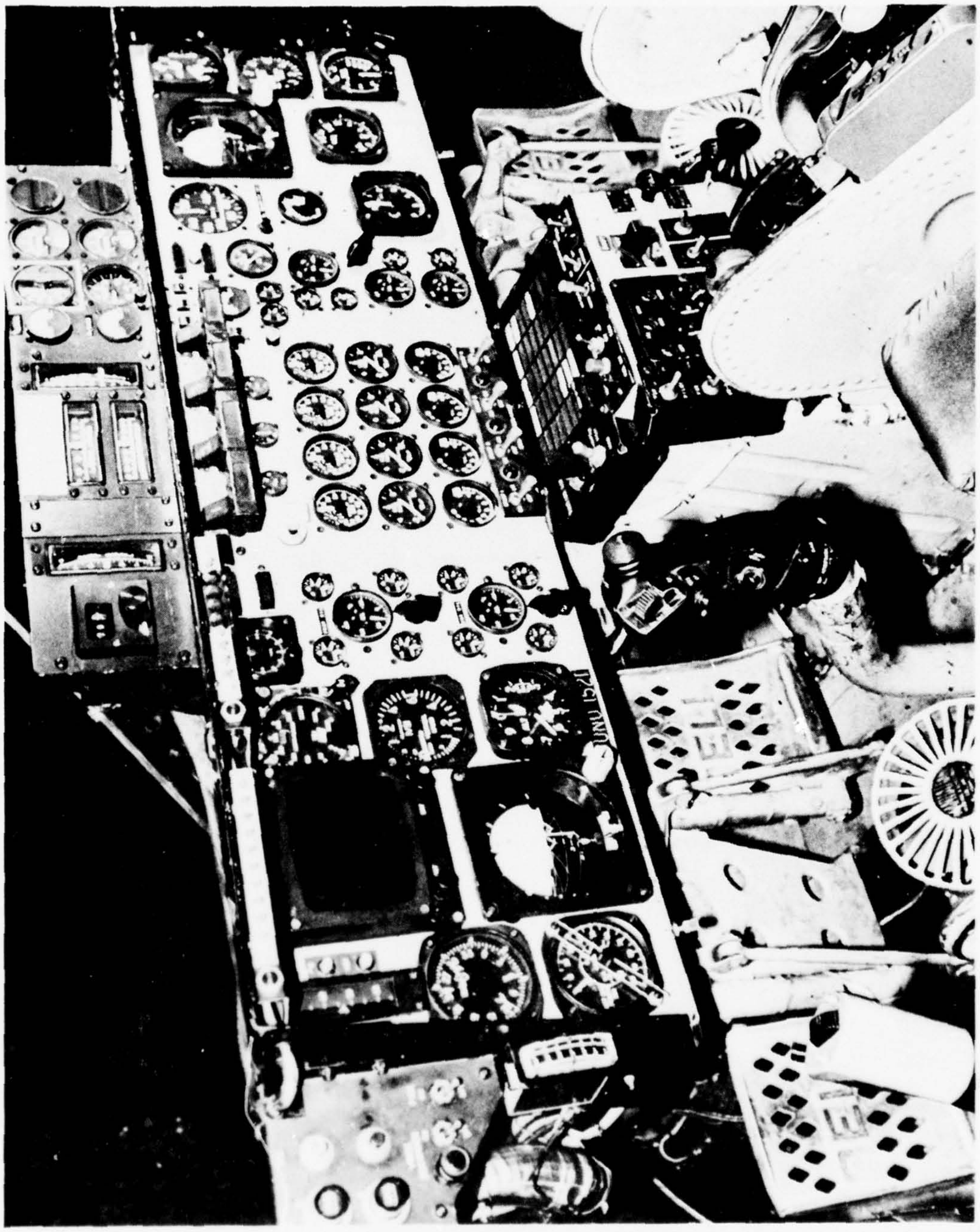


Figure V-3 EVALUATION PILOT STATION (HUD NOT INSTALLED)

During VSS operation, the evaluation pilot occupies the left-hand seat in the cockpit. The system operator, who also serves as the safety pilot, occupies the right-hand seat. The evaluation pilot's inputs, in the form of electrical signals, operate the appropriate right-hand flight controls through the electrohydraulic servos. In addition to the evaluation pilot's inputs, signals proportional to aircraft motion and relative wind variables (for example, pitch rate and angle of attack are fed back to move the right-hand controls in the required manner and thus modify the aircraft's response characteristics as desired. The response-feedback and input gain controls, located beside the safety pilot, are used to set up the simulation configurations in flight (Figure V-4). Note that the evaluation pilot cannot feel the basic X-22A control motions caused by the variable stability system.

Figure V-5 shows schematically a simplified example of the X-22A variable stability mechanization. This example illustrates how the desired values of the derivatives $M_{\delta_{es}}$ and M_{α} are achieved with this response feedback technique. Figure V-6 shows the full schematics for the four control-channels of the VSS, including the artificial feel system.

Unique Features of the X-22A

1. Feedforward Flight Control System

One unique feature of the X-22A is the Feedforward Flight Control System (FFCS). This is a limited authority, precision control system which acts like a vernier on the basic X-22A flight control system during VSS operation. The FFCS makes it possible to achieve extremely high precision in positioning the actuators for the X-22A aerodynamic controls - propeller pitch and elevon angle. Such control system precision is required for the satisfactory operation of the "closed-loop" VSS airplane.

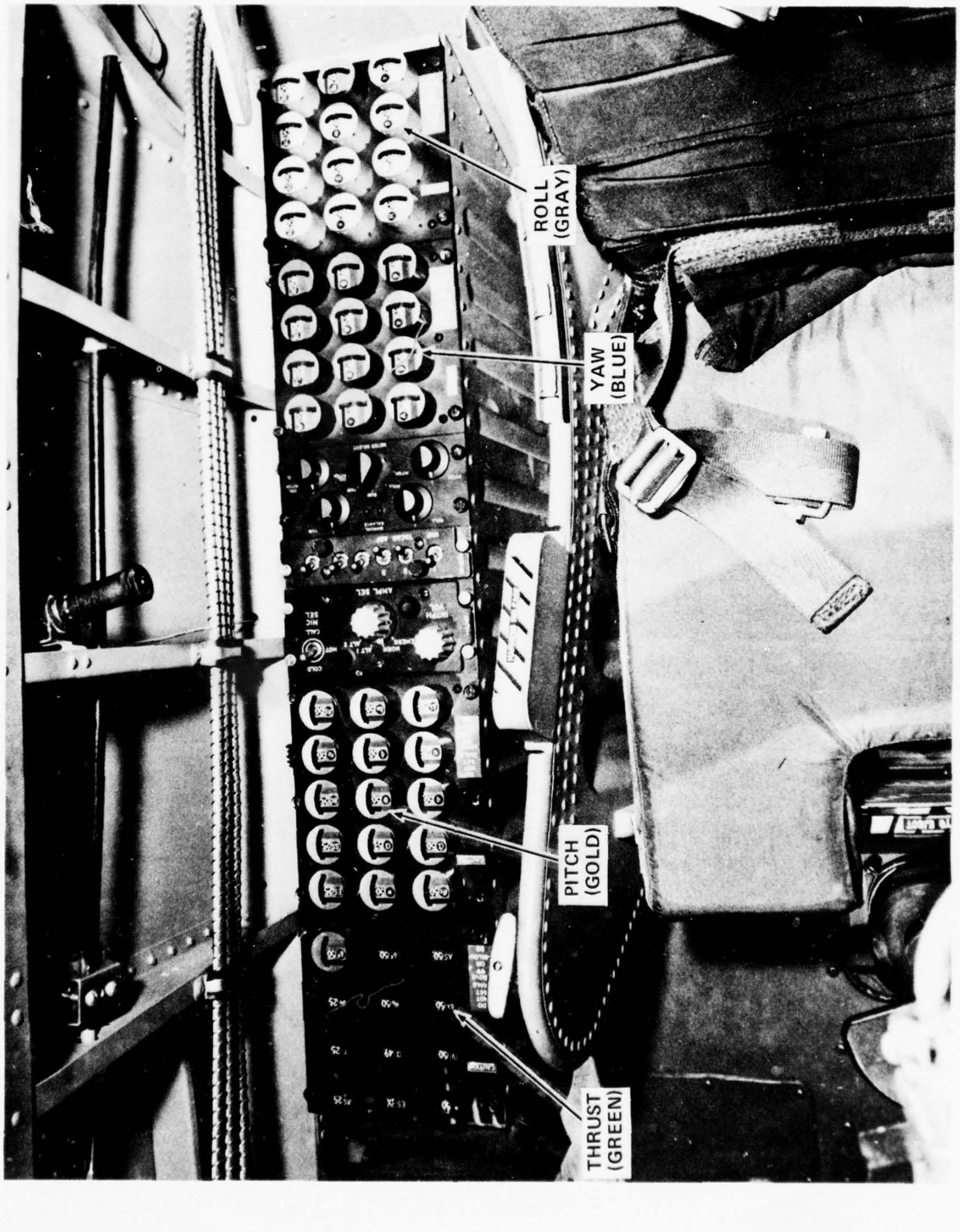
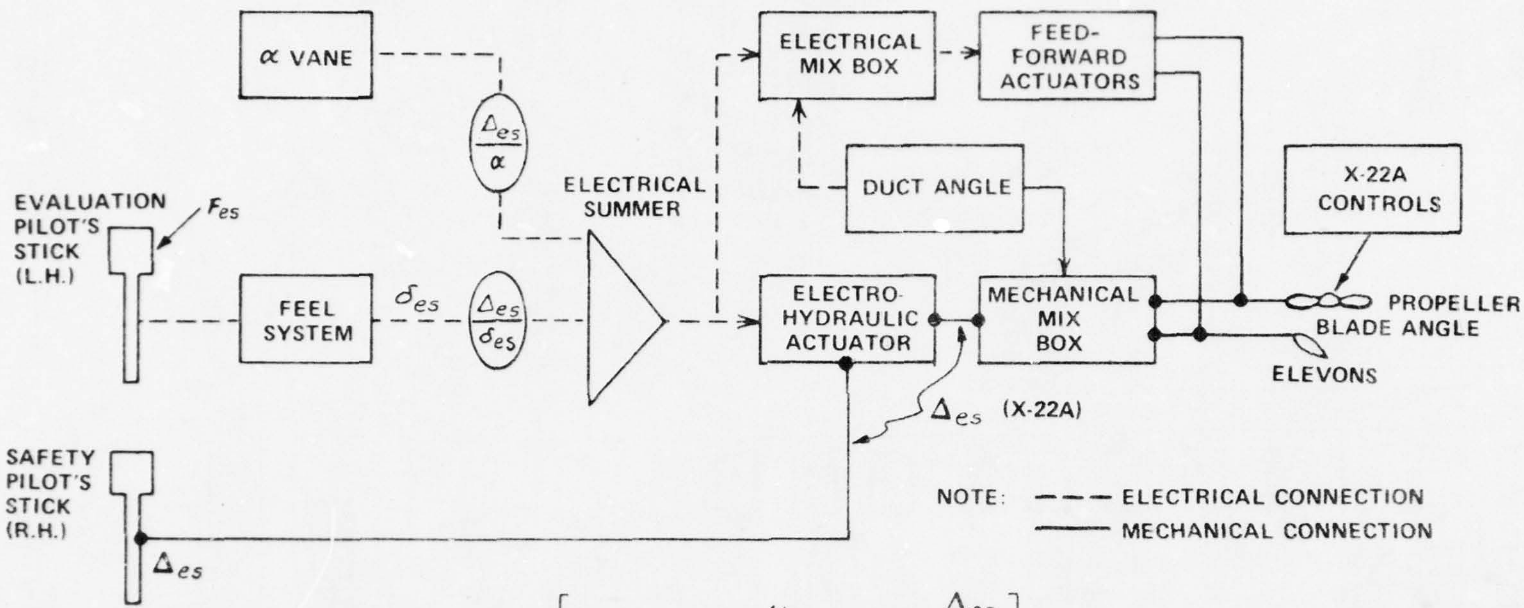


Figure V-4 VSS GAIN CONTROLS IN X-22A COCKPIT



$$M_{\alpha\,(\text{SIMULATED})} = \left[M_{\alpha(X-22A)} \pm M_{\Delta_{es}(X-22A)} \frac{\Delta_{es}}{\alpha} \right]$$

$$M_{\delta_{es}\,(\text{SIMULATED})} = \left[M_{\Delta_{es}(X-22A)} \frac{\Delta_{es}}{\delta_{es}} \right]$$

Figure V-5 SIMPLIFIED EXAMPLE OF THE X-22A VARIABLE STABILITY SYSTEM MECHANIZATION

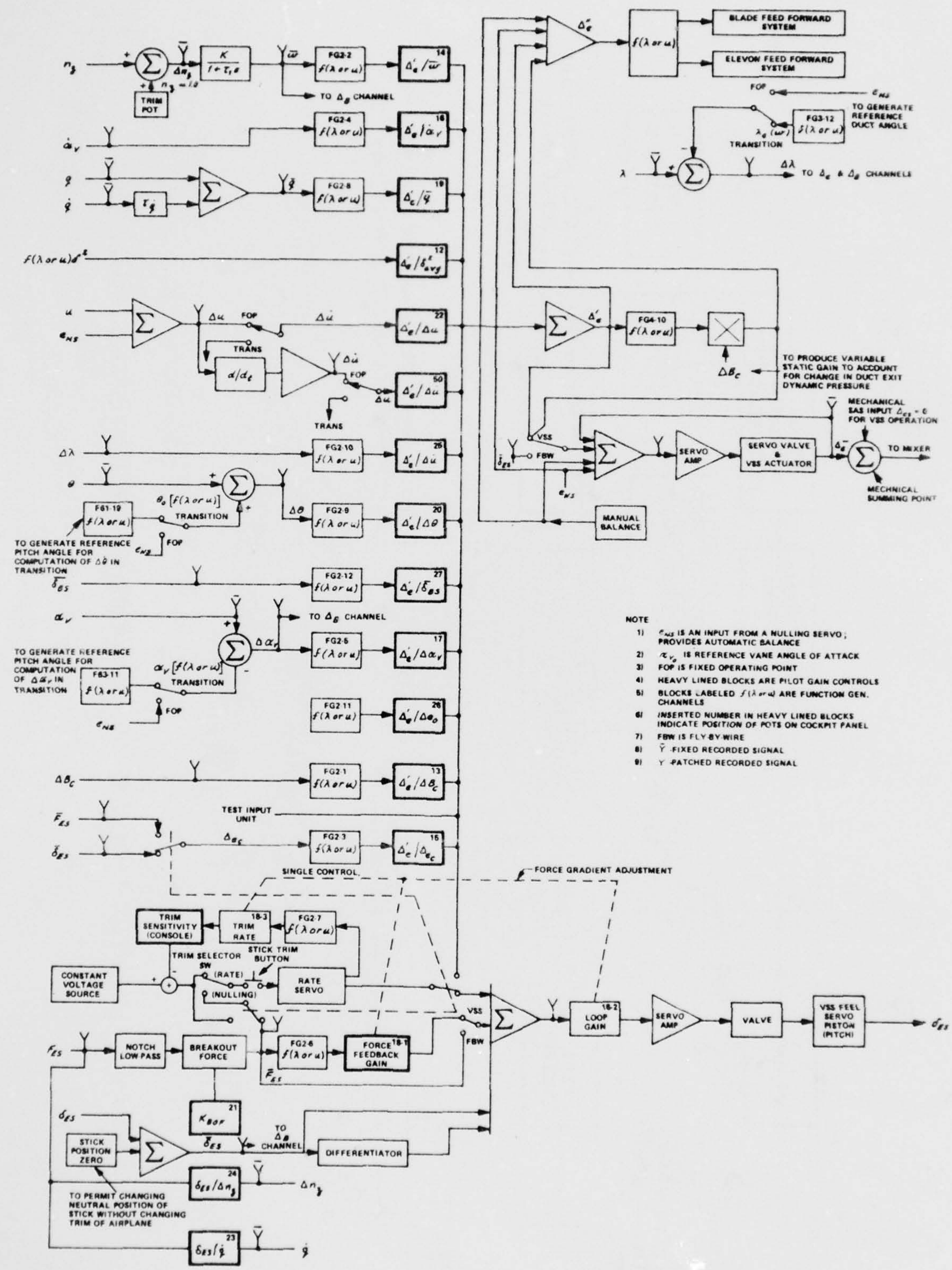


Figure V-6(a) X-22A VSS BLOCK DIAGRAM - PITCH CONTROL

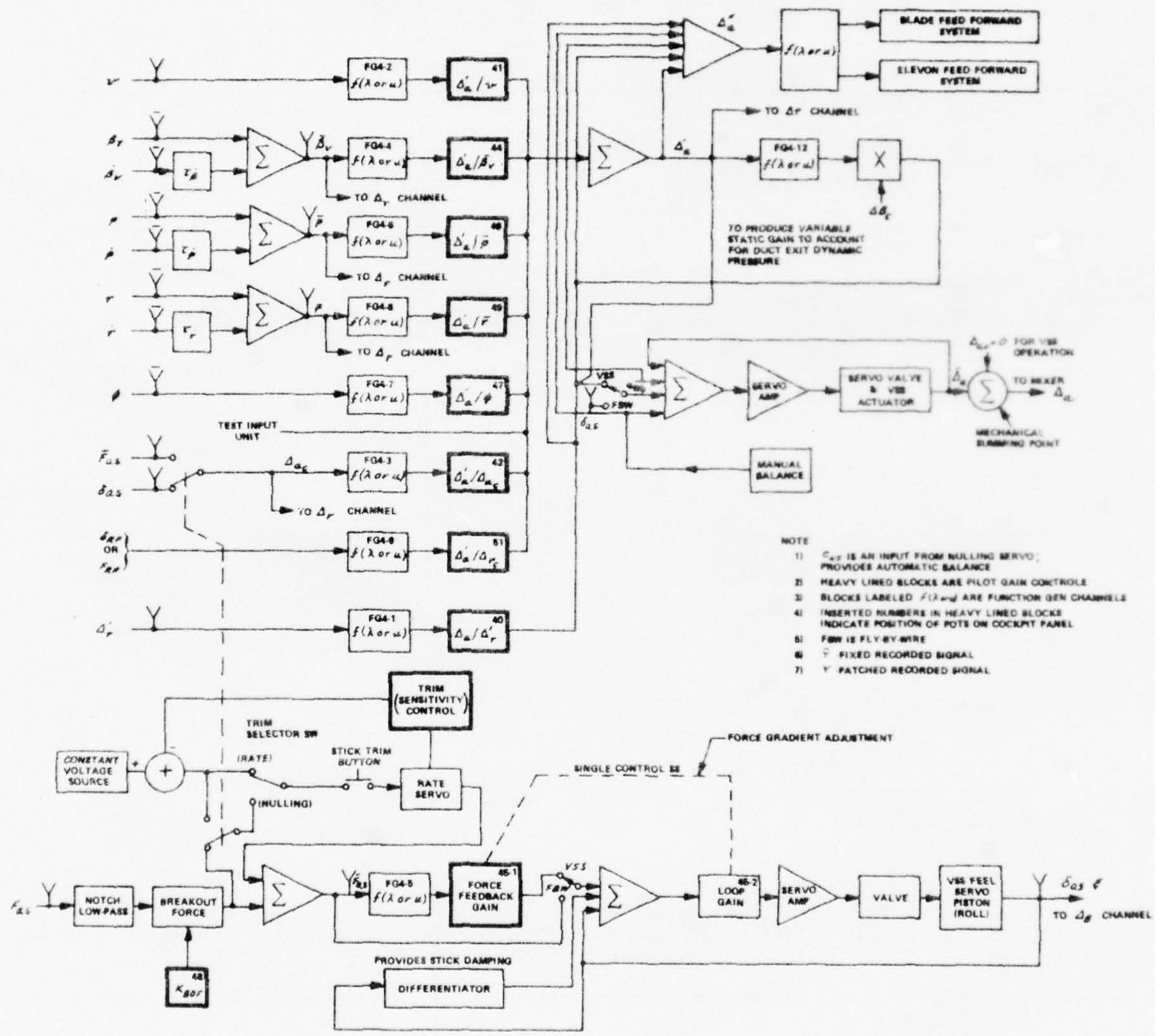


Figure V-6(b) X-22A VSS BLOCK DIAGRAM - ROLL CONTROL

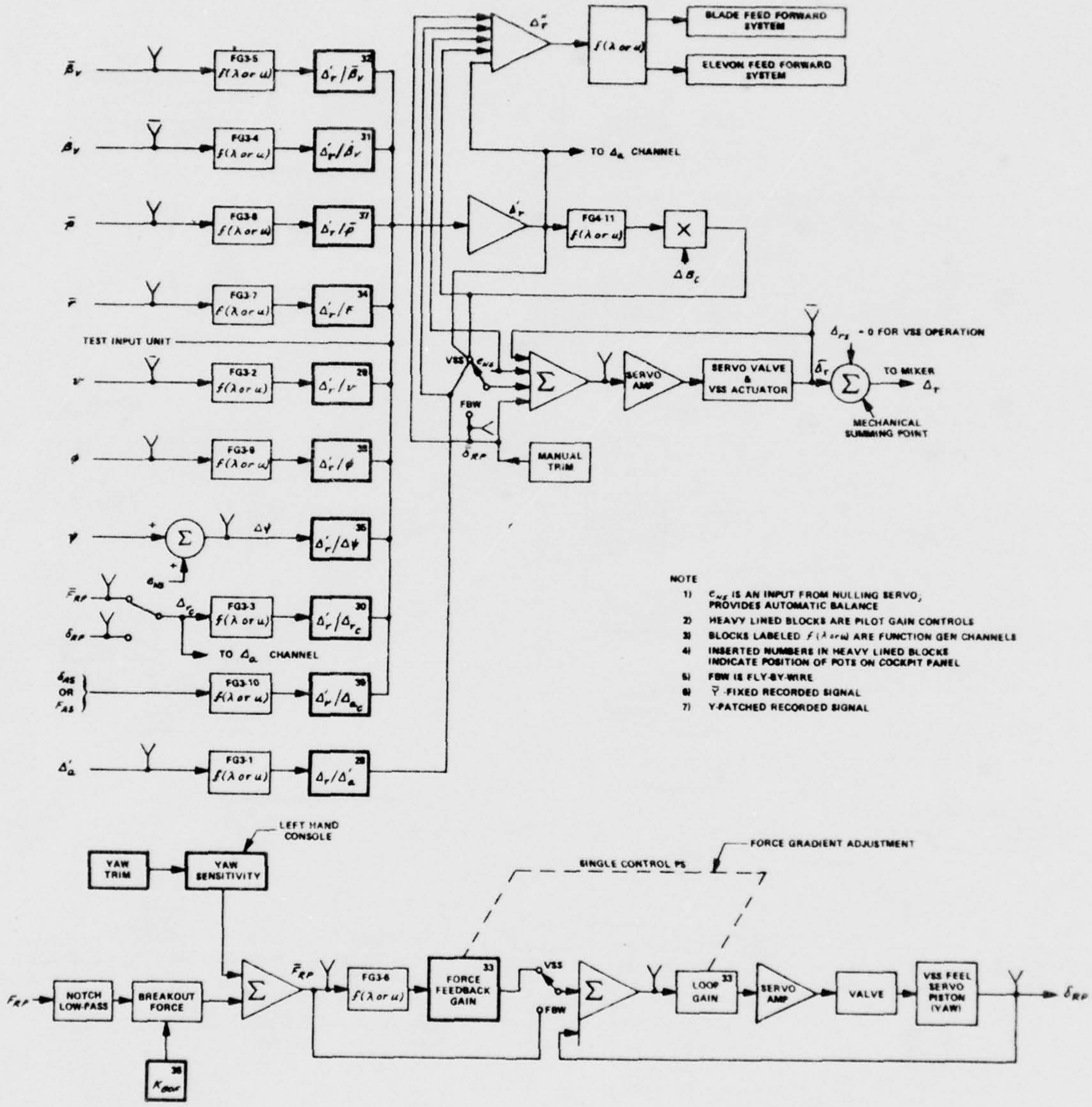


Figure V-6(c) X-22A VSS BLOCK DIAGRAM - YAW CONTROL

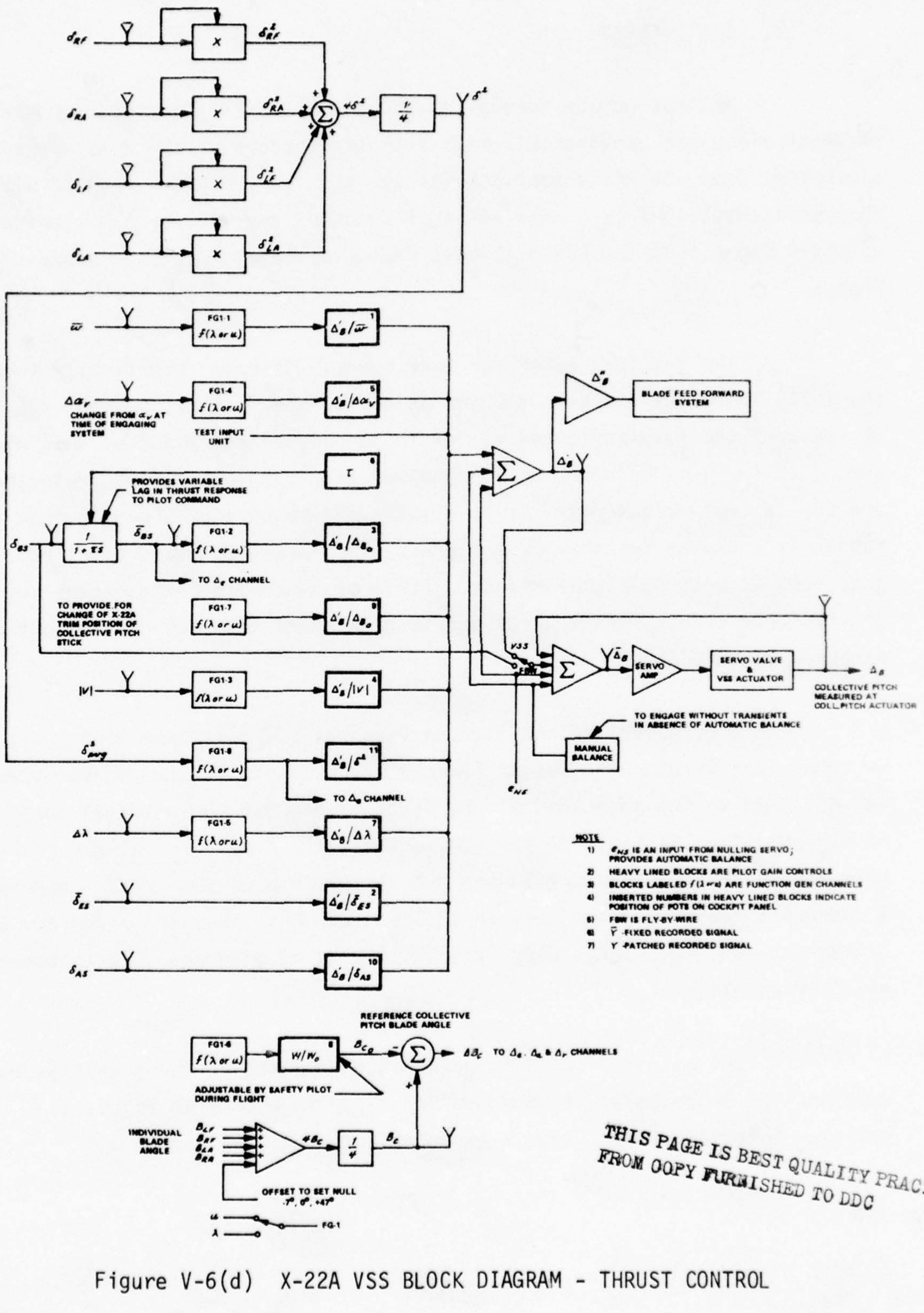


Figure V-6(d) X-22A VSS BLOCK DIAGRAM - THRUST CONTROL

2. LORAS

Another unique feature of the X-22A VSS is that the response feedback gains are programmable with velocity throughout the full range of airspeeds, from -30 knots rearward through zero to 150 knots forward airspeed. This is accomplished by a multi-channel function generator which receives its airspeed input from the LORAS (Linear Omnidirectional Resolving Airspeed System).

The original LORAS was developed at Calspan specifically to meet the X-22A VSS requirements. Mounted on top of the vertical tail of the X-22A, it measures the total airspeed vector in the horizontal plane of the rotating arm, $\sqrt{u^2 + v^2}$. This vector is resolved into the longitudinal velocity (u) and the lateral velocity (v). A significant feature of LORAS is that its output is a linear function of airspeed. This means it measures airspeeds near zero as well as higher speeds. It is also notable that, except for density corrections, static pressure is eliminated from the measurement of airspeed with LORAS.

A much smaller and lighter version, LORAS II, was later developed by LORAS Instruments, Inc. under license to Calspan. It then became possible to add LORAS to the nose boom of the X-22A to measure the vertical component of airspeed (w) for use in the VSS, especially in hovering flight. The nose-boom-mounted LORAS, rotating in the X-Z plane, senses $\sqrt{u^2 + w^2}$ and produces a redundant measurement of u in addition to w. Thus the X-22A Air Data System can sense all three body axis components of airspeed in both hovering and forward flight.

The original LORAS is shown on top of the vertical tail in Figure V-1, and the later model is shown on the X-22A nose boom in Figure V-7. More detailed information on LORAS is given in References 35 and 36 .

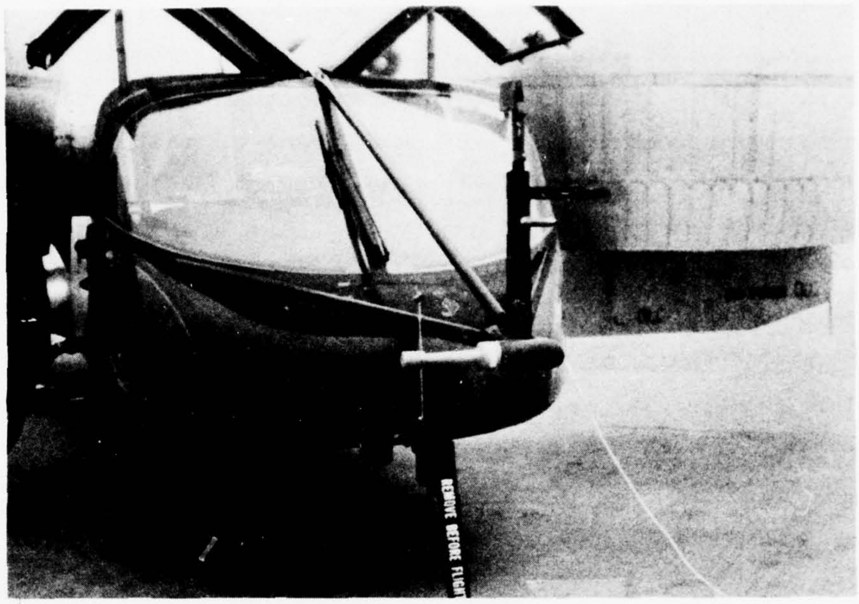


Figure V-7 X-22A NOSE LORAS

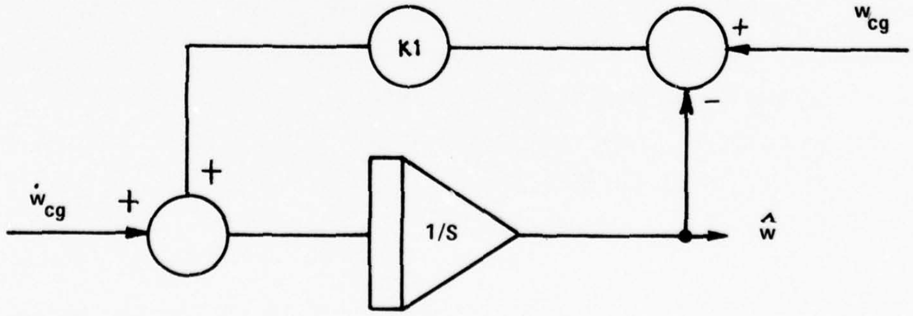


Figure V-8 VERTICAL VELOCITY COMPLEMENTARY FILTER BLOCK DIAGRAM

LORAS Signal Processing

Accurate sensor data with low noise content is required for in-flight simulation in both control and display applications. Air data sensors are difficult to locate on the surface of an airframe in positions free from perturbed air flow. This is particularly true of vertical short takeoff and landing aircraft where the aircraft geometry changes as a function of airspeed and where, at low altitudes, "ground effect" can disturb normal air flow patterns. Generally the air data sensors cannot be conveniently located at the center of gravity (c.g.) of the aircraft; therefore position corrections must be added to the air data measurements to obtain the airspeed at the c.g. of the aircraft.

As noted above, lateral (v) and longitudinal (u) airspeeds are sensed by the tail-mounted LORAS while vertical (w) and longitudinal (u) airspeed are sensed by the nose LORAS installation. The longitudinal and lateral airspeed signals derived from the tail LORAS are filtered by simple second-order, low-pass filters. The resultant filtered data is satisfactory for both control system augmentation and display presentation. Only position corrections are necessary to translate data measurements to the aircraft c.g. Vertical airspeed data obtained from the nose LORAS is sensed along with unwanted noise. The noise bandwidth was found to be between 2.5 to 24 Hertz. The noise level severely restricted the useful range of vertical velocity feedback gain available for control system augmentation. A portion of the noise, a 24-Hertz signal due to the rotational speed of the LORAS, is proportional to the total magnitude of airspeed represented by $\sqrt{u^2 + w^2}$. However, the predominant lower frequency noise content is attributed to turbulence effects. Unacceptable phase shift resulted when low-pass filters were implemented to reduce the noise level.

A simple first-order, complementary filter blending inertial information and vertical velocity (w) was mechanized and is represented by equations (V-1), (V-2) and (V-3).

$$\hat{w} = \frac{w_{c.g.}/K_1 + w_{c.g.}}{s/K_1 + 1} \qquad \text{(V-1)}$$

$$\dot{w}_{c.g.} = N_z + uq \qquad \text{(V-2)}$$

$$w_{c.g.} = Kw + \ell q \qquad \text{(V-3)}$$

where $\hat{w}$ = filtered vertical velocity

$w_{c.g.}$ = unfiltered vertical velocity at c.g.

$\dot{w}_{c.g.}$ = rate of change of vertical velocity

K_1 = filter loop gain

ΔN_z = vertical acceleration less gravitational acceleration

u = longitudinal airspeed

q = pitch rate

K = aerodynamic flow effect gain

w = unfiltered vertical velocity at nose

ℓ = longitudinal distance of nose LORAS from the c.g.

A block diagram of the filter implementation is shown in Figure V-8. The filter input and output signal noise characteristics are presented in Figure V-9A, B and C. For comparison, a vertical velocity (w_{vane}) was derived from an

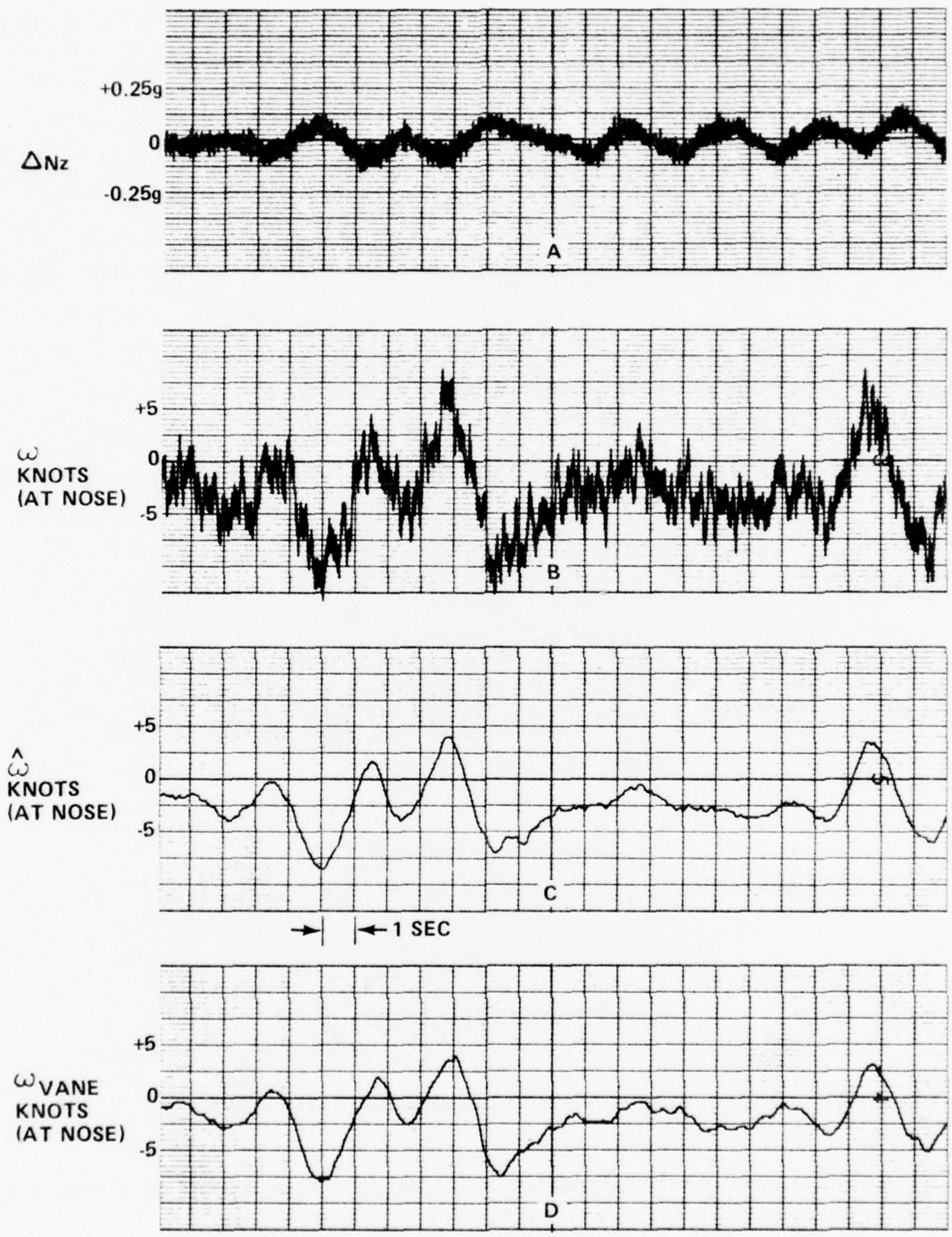


Figure V-9 VERTICAL VELOCITY INPUT AND OUTPUT SIGNAL NOISE CHARACTERISTICS

angle of attack vane sensor signal (α) and is shown in Figure V-9D. The computation for w_{vane} is:

$$w_{vane} = \alpha \cdot u \qquad \text{(V-4)}$$

The filter loop gain constant (K1) and aerodynamic flow effect gain (K) were determined empirically to minimize filter output noise and error between w and w_{vane}. The filtered vertical velocity w proved to be satisfactory for control system application throughout the entire flight profile, including ground effect and rollout after touchdown on a STOL landing.

Wind Direction Indication

Wind direction is a useful cue for the final stages of the approach and during the hover task. A wind vector was derived by summing the heading reference ground speed vectors with tail LORAS airspeed information. A wind direction indication (refer to Figure 6-2) was mechanized by computing body axis wind vector angle and presenting the angular information on the HUD.

3. X-22A Guidance and Display Equipment

In addition to the variable stability and control capability afforded by the VSS, the X-22A aircraft systems include guidance and display equipment to permit variable guidance and variable display investigations. These systems consist of several computational units plus both a Head-Up-Display (HUD) unit and a Head-Down-Display (HDD) cathode ray tube; basic elements of these systems are summarized below.

1. Microwave Landing System (the MLS ground equipment is described in more detail later in this Appendix). This system was developed as a portable tactical landing system by the U.S. Army Electronics Command (ECOM) and built by the AIL Division of Cutler-Hammer, Inc. It operates at approximately 15 GHz, employs the scanning beam technique and has co-located DME. The airborne equipment in the X-22A (Figure V-10) decodes absolute azimuth

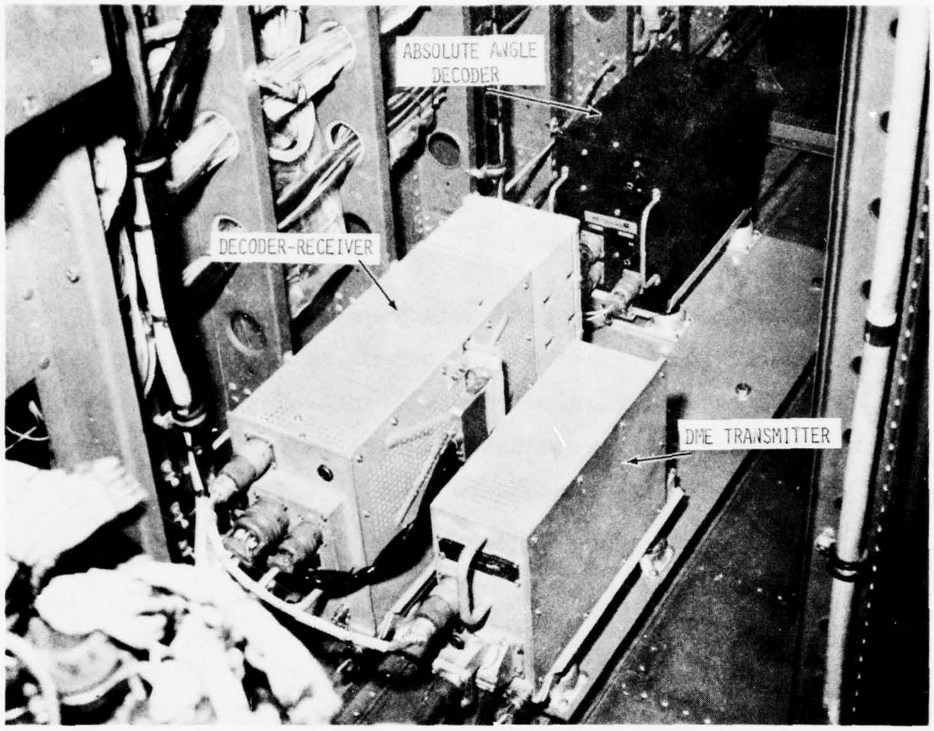


Figure V-10 AIRBORNE MLS EQUIPMENT

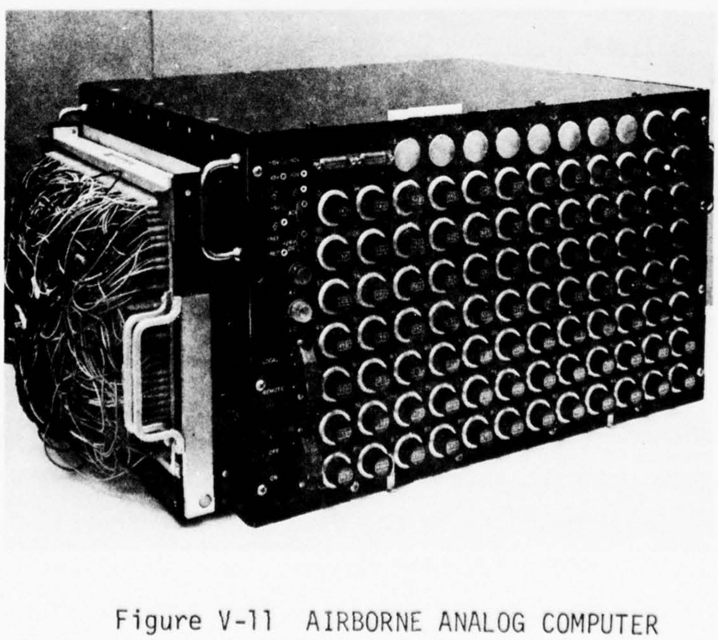


Figure V-11 AIRBORNE ANALOG COMPUTER

and elevation angle information from the landing site as well as error information from the approach path and selected glide slope. The absolute position data from the MLS are blended with on-board accelerometer data through complementary filters to obtain smoothed position data for guidance.

2. Airborne Analog Computer (Figure V-11). This unit performs guidance data transformations, guidance command computations, and flight director computations. It also permits additional stability/control variations including limited model-following (command prefiltering). Fourteen (14) potentiometers are located in the cockpit to provide in-flight variations if desired. The functional elements of the computer are summarized in Table V-1 below.

TABLE V-1

ANALOG COMPUTER FUNCTIONAL ELEMENTS

Quantity	Computing Element
20	Integrators
76	Summer/Inverters
32	Multipliers
12	Balance-Holds
10	Diode Function Generators
10	Special Circuits
10	Filters
76	Grounded Potentiometers
20	Floating Potentiometers
62	Resistor Groups
10	Relays

Figure V-12 gives the programming diagrams for the computer as implemented in this experiment; Table V-2 provides a representative set of potentiometer values (used for the last five flights of the program). A more complete description of the computer design is given in Reference 37 .

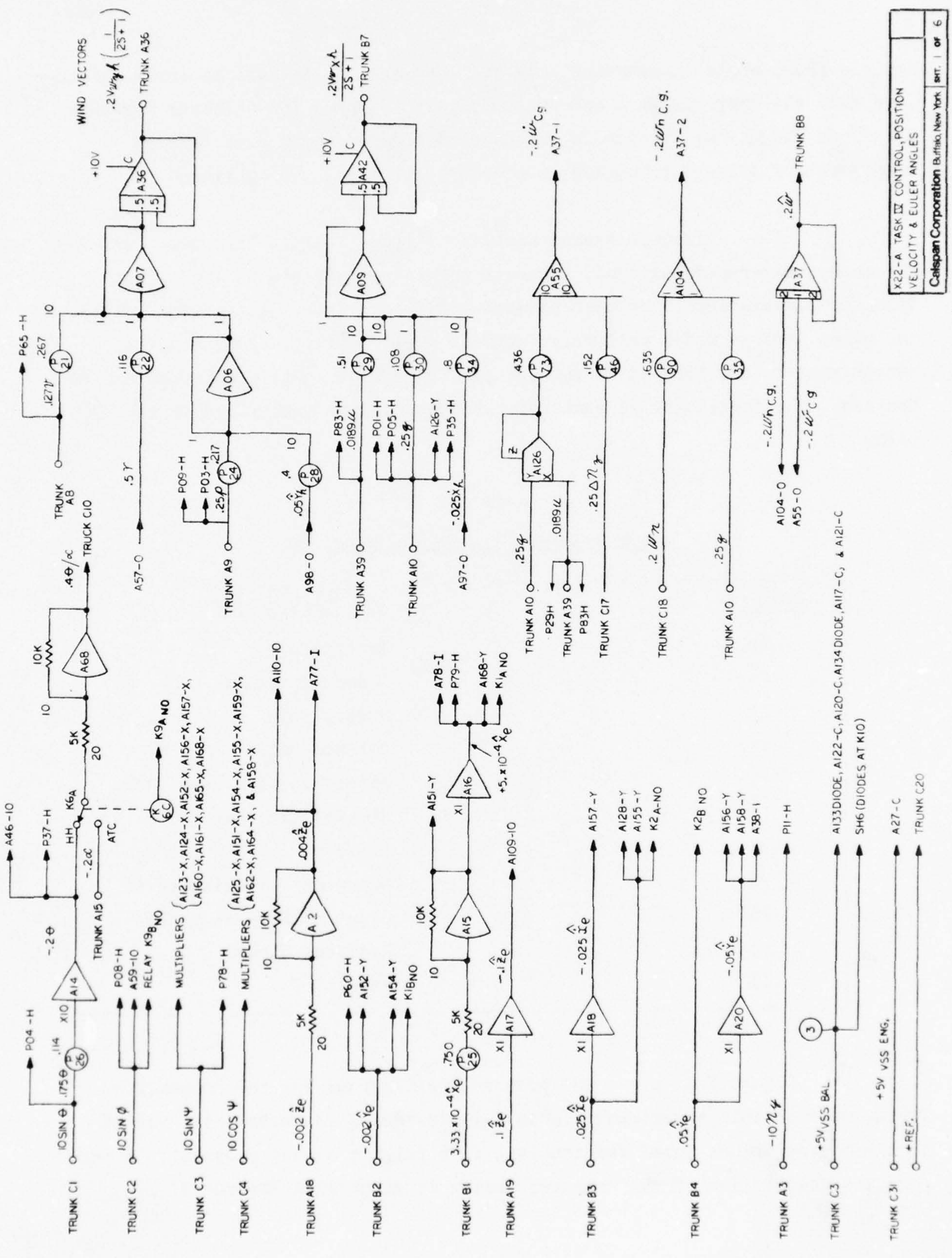


Figure V-12 TASK IV ANALOG COMPUTER DIAGRAM (Sheet 1 of 6)

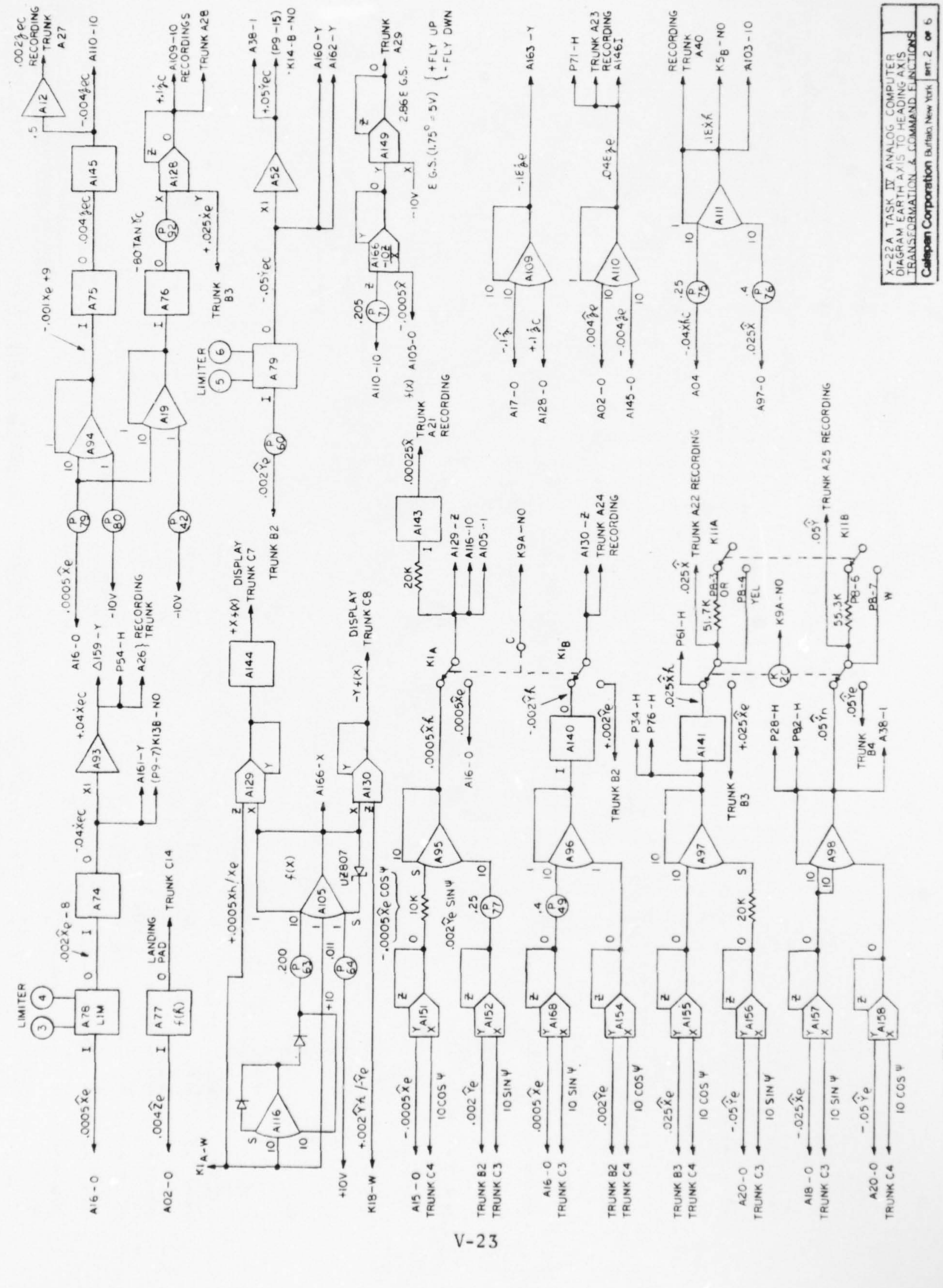


Figure V-12 TASK IV ANALOG COMPUTER DIAGRAM (Sheet 2 of 6)

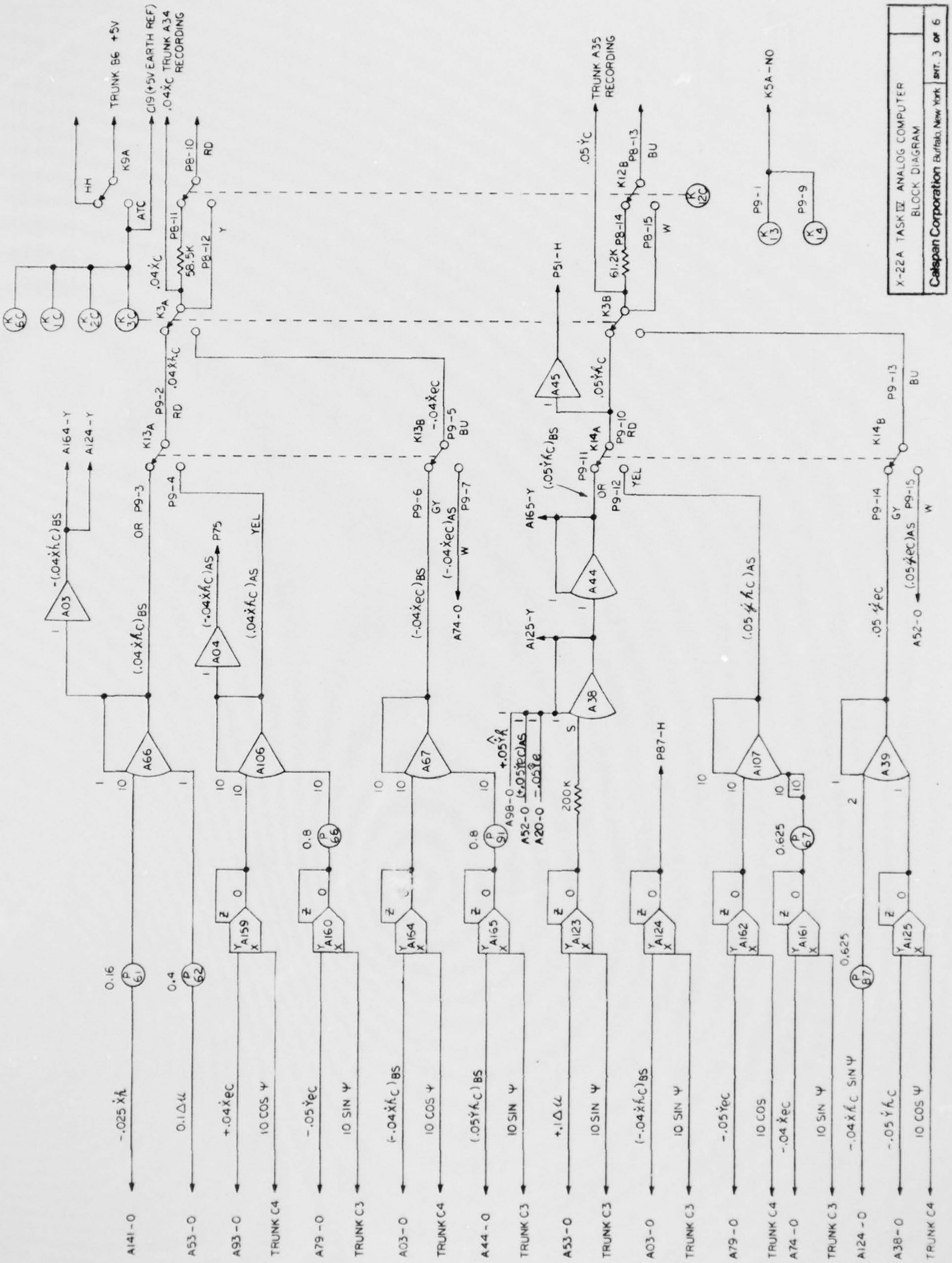


Figure V-12 TASK IV ANALOG COMPUTER DIAGRAM - GUIDANCE COMPUTATIONS (Sheet 3 of 6)

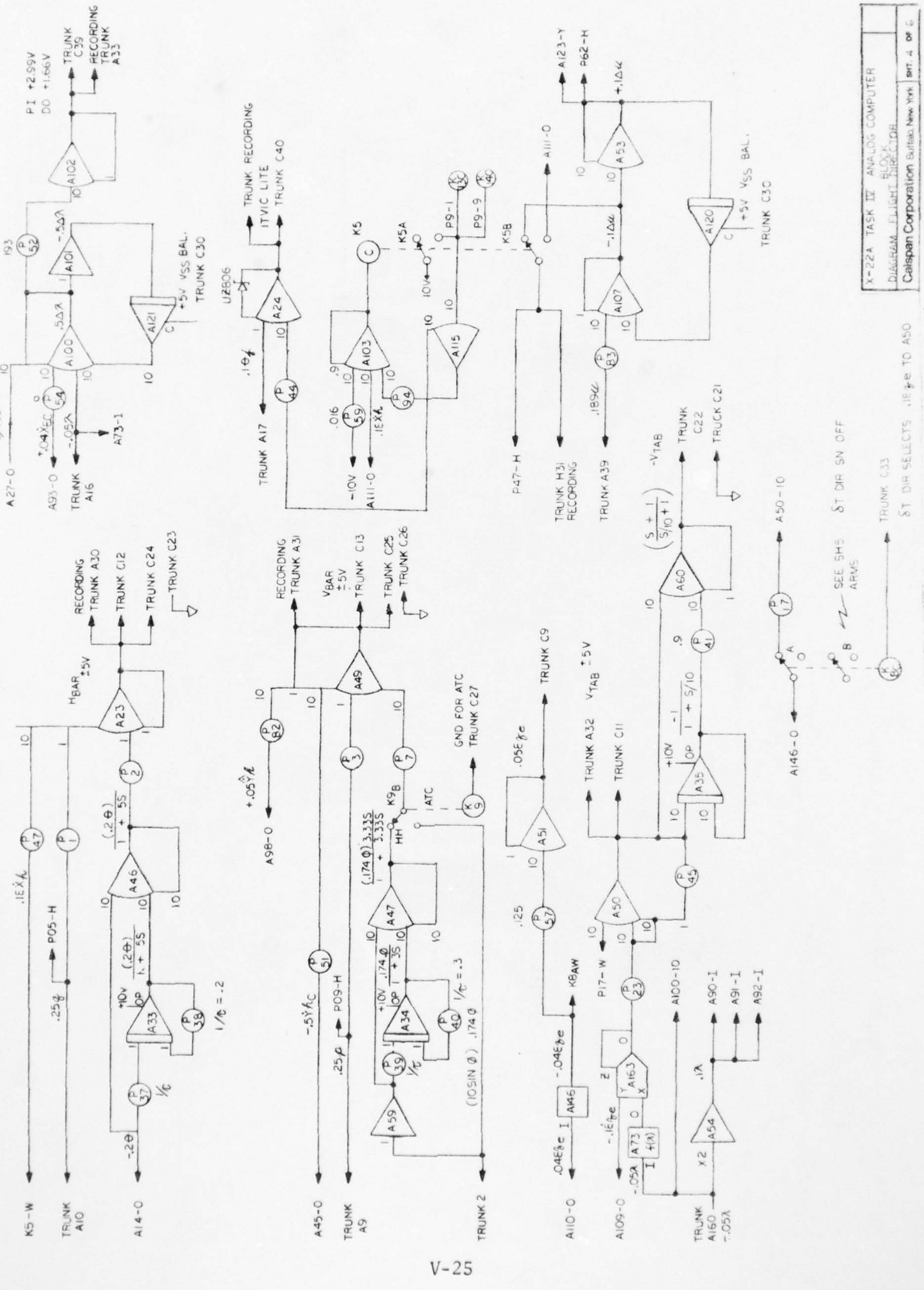


Figure V-12 TASK IV ANALOG COMPUTER DIAGRAM (Sheet 4 of 6)

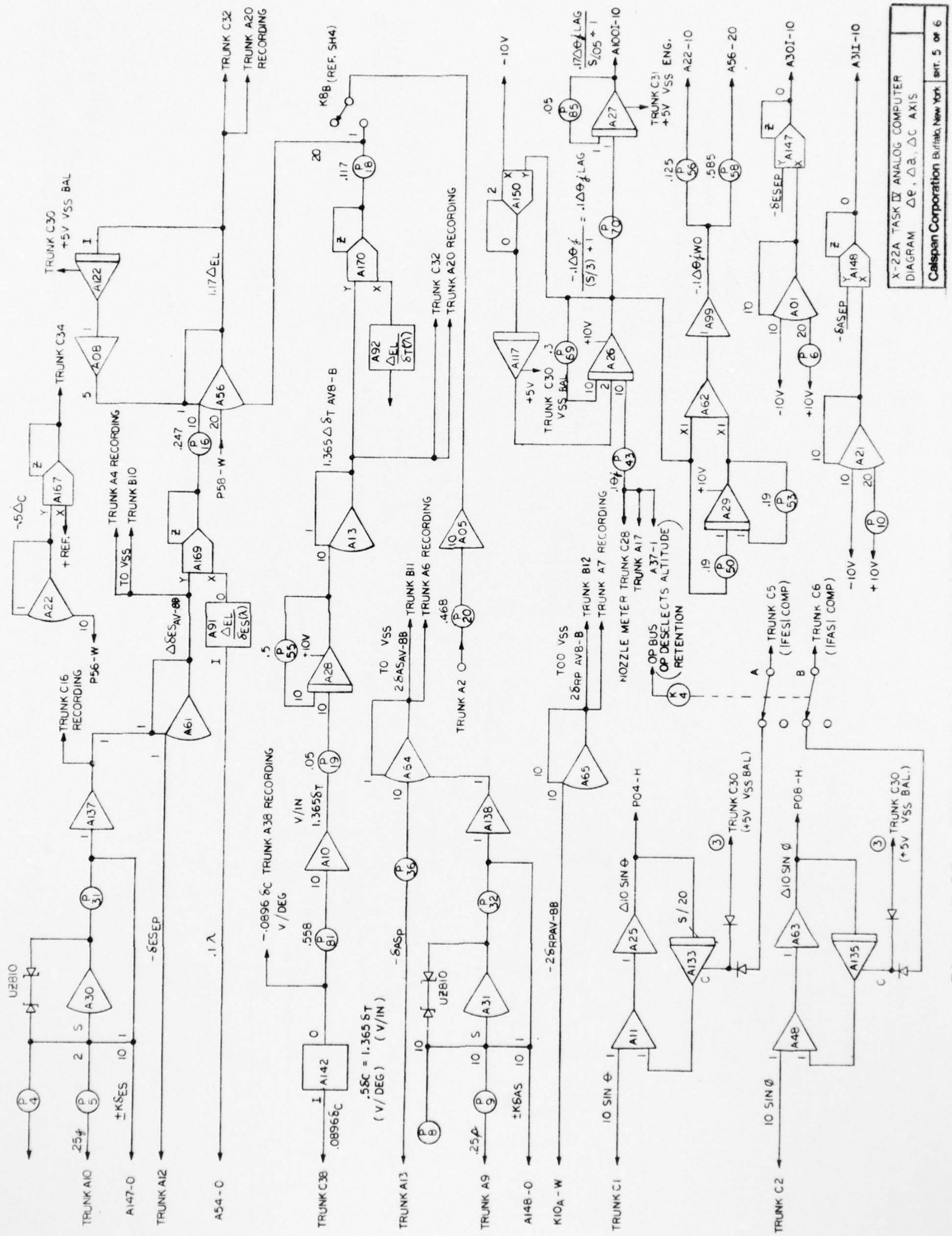


Figure V-12 TASK IV ANALOG COMPUTER DIAGRAM (Sheet 5 of 6)

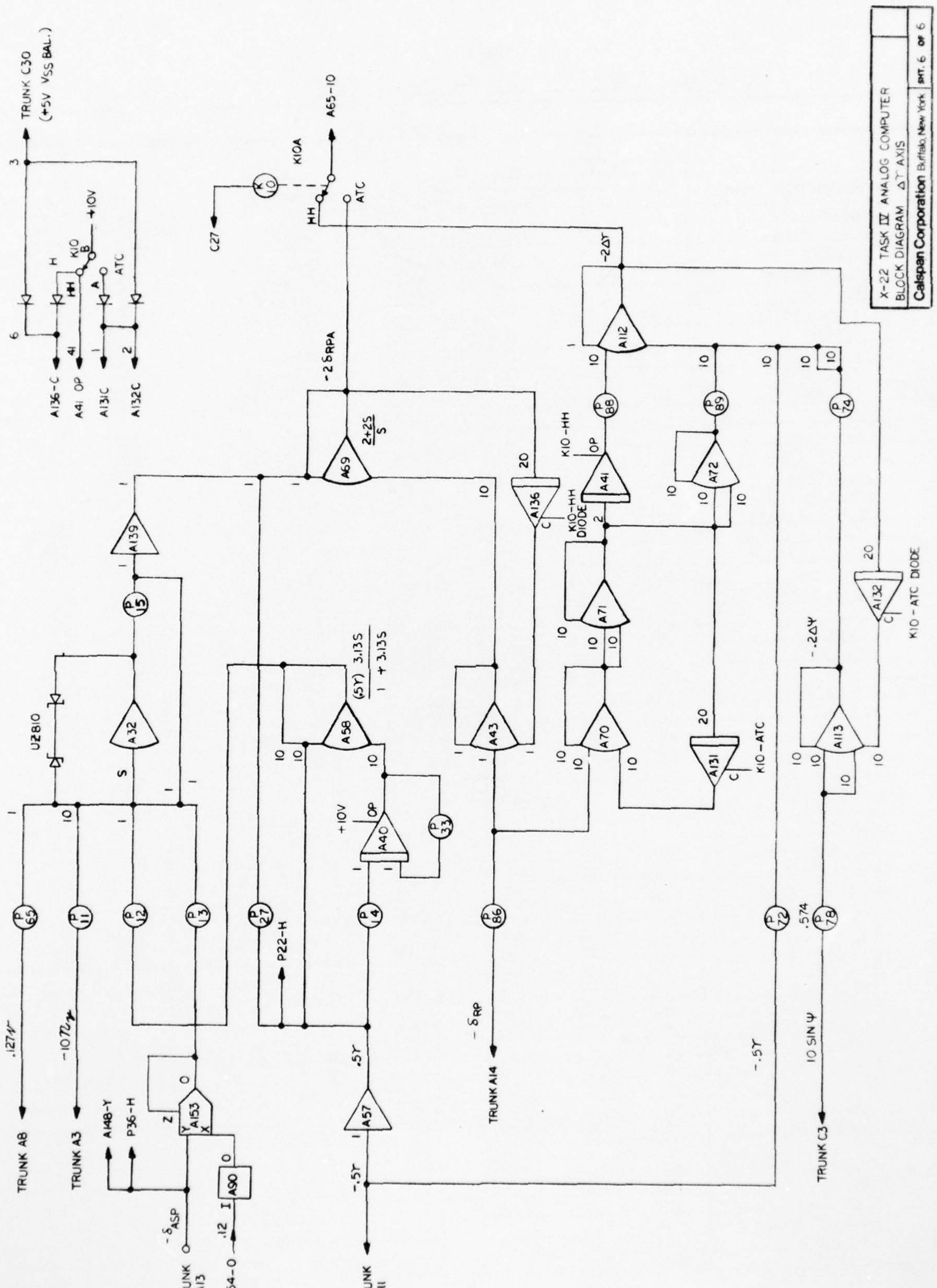


Figure V-12 TASK IV ANALOG COMPUTER DIAGRAM (Sheet 6 of 6)

TABLE V-2

X-22A ANALOG COMPUTER POT LIST (Flts. 177-181)

	POT NO.	PARAMETER	SCALE	RATIO	POT SET	LOAD ←	LOAD →	POT NO.	PARAMETER	SCALE	RATIO	POT SET
	P01	HBAR/q			*	10K	10K	P55	δ_T Lag		.500	562
	P02	HBAR/$\theta_{w.o}$			*	100K	10K	P56	$\Delta c/\Delta\theta_j$		.125	132
	P03	VBAR/p			*	100K	10K	P57	Diamond/ϵ_j		.125	132
C	P04	δ_{ES} AV8/$\Delta\theta$	SAS		*	10K	5K	P58	ΔEL/$\Delta\theta_j$		.585	706
O	P05	δ_{ES} AV8/q	SAS		*	50K	10K	P59	.01$\epsilon\dot{x}h$+	1.5	.016	016
C	P06	$\pm\Delta\delta_{ES}$AV8/δ_{ES}	SAS	500/	500/	10K	5.9K	P60	$\dot{y}_{ec}/y_e$		.283	337
K	P07	VBAR/ϕ			*	10K	10K	P61	.25$\dot{x}h$		.160	171
P	P08	δ_{AS} AV8/$\Delta\phi$	SAS		*	10K	100K	P62	.1Δu		.400	405
I	P09	δ_{AS} AV8/p	SAS		*	10K	10K	P63	f(y) Gain		.200	217
T	P10	$\pm\delta_{AS}$AV8/δ_{AS}	SAS	500/	500/	10K	100K	P64	$\frac{y}{z+k}$ OFFSET		.011	011
	P11	δ_{RP}/n_y	SAS		0	10K	100K	P65	$\Delta r/v$			000
	P12	$\delta_{RP}/\tau_{w.o.}$	SAS			100K	10K	P66	.05$\dot{y}_{ec}$ sin ψ		.800	851
	P13	δ_{RP}/f(λ)δ_{AS}	SAS		0	100K	5K	P67	.8$\dot{x}_{ec}$ sin ψ		.625	744
	P14	$\delta_{RP}/(\tau)\gamma_{w.o.}$	SAS			100K		P68				
	P15	δ_{RP}LIMITER	SAS		150	20K	10K	P69	$\Delta\theta_j$ Lag		.300	333
	P16	ΔEL/f(λ)$\cdot\Delta\delta_{ES}$		.247	271	10K	100K	P70	$\Delta\theta_j$Lag/$\frac{s}{.05}+1$		.098	098
	P17	VTAB/ϵ_j	(δ_T DIR SW ON)	.0625	065	10K	∞	P71	164 GS		.205	205
	P18	ΔEL/f(λ)$\cdot\Delta\delta_T$		.171	198	5K	10K	P72	$\Delta r/r$ (H.H)		.0489	050
	P19	δ_T Gain		.050	051	10K	10K	P73	.436μq		.436	450
	P20	COLL ELEVON TIU			000	10K	5K	P74	20(.2$\Delta\psi$/2Δr)		.0436	045
	P21	Vwyh/v		.267	295	10K	10K	P75	.4 $\dot{x}_{hc}$		.250	275
	P22	Vwyh/r		.116	116	100K	10K	P76	.25 $\dot{x}_h$		.400	450
	P23	VTAB/f(λ)ϵ_j			999	5K	10K	P77	.002 y_e sin ψ		.250	275
	P24	Vwyh/p		.217	219	100K	5K	P78	.2ψ		.574	696
	P25	.0005 $\hat{z}_e$		.750	847	5K	5K	P79	(.001x_e+9)/.0005x_e		.200	236
	P26	.2θ		.114	120	10K	100K	P80	+9V OFFSET		.895	894
	P27	$\Delta r/r$		000	000	100K	10K	P81	5.58(.09δ_c)		.558	624
	P28	Vwyh/Y_h		.400	450	10K	10K	P82	VBAR/$\dot{Y}_h$		.235	257
	P29	Vwyh/u		.529	649	5K	10K	P83	.0189 u		.529	593
	P30	Vwyh/q		.216	218	100K	100K	P84				
	P31	δ_{ES} LIM	SAS		085	20K	100K	P85	$\Delta\theta_j$ Lag/$\frac{s}{.05}+1$		.050	050
	P32	δ_{AS} LIM	SAS		125	20K	9.09K	P86	$\Delta r/\delta_{RP}$		.100	106
	P33	(τ) $\delta_{RP}/\tau_{w.o.}$		.319	323	100K	50K	P87	.08 $\dot{x}_{hc}$ sin ψ		.625	639
	P34	Vwxh/$\hat{x}_h$		.800	851	10K	10K	P88	$\Delta r/\int\Delta\delta_{RP}$ H.H.			275
	P35	.186 (.25q)		.186	201	10K	10K	P89	$\Delta r/\Delta\delta_{RP}$ H.H.			275
	P36	δ_{AS}AV8/δ_{AS}		.200	217	10K	10K	P90	.635(.2ω)		.635	701
	P37	1/τ(θ)		.200	200	100K	10K	P91	.05u_{hc} sin ψ		.800	851
	P38	1/τ(θ)		.200	200	100K	∞	P92	.375(80 tan γ_c)		.375	375
	P39	1/τ(ϕ)		.300	303	100K		P93				
	P40	1/τ(ϕ)		.300	303	100K	10K	P94	$\epsilon\dot{x}h$ HYST			200
	P41	.9($\frac{1}{1+s/10}$) 1ϵ_j		.900	929½	10K		P95				
	P42	-.001x_e + 8.5		845	849	100K		P96				
	P43	.1θ_j Gain	λ45°/λ15° .3/.514	λ45° 333	λ15° 577	10K		X_{OFFSET}	(6'/DIV	IN FRONT	OF MLS >	500)
	P44	ITVIC LITE COMP		.031	031	10K		Y_{OFFSET}	0 ft	500	(Not working)	
	P45	VTAB Gain			380	100K		Z_{OFFSET}	0 ft	500		
	P46	.152(2.5Δn_z)		.152	162	10K		LIMITER				
	P47	HBAR/$\epsilon\dot{x}_h$		.150	160	10K		P3	+.002 x_e + 8			000
	P48					10K		P4	-.002 x_e + 8			000
	P49	.002x sin ψ		.400	424	20K		P5	-.05 $\dot{y}_{ec}$			641
	P50	$\Delta\theta_j$ w.o.		.190	193	100K		P6	+.05 $\dot{y}_{ec}$			641
	P51	VBAR/$\dot{y}_{hc}$		.235	257	10K						
	P52	λ to 90°	CONT	.179	193			* Per Flt. Plan				
	P53	$\Delta\theta_j$ w.o.		.190	193	100K						
	P54	$\lambda/\dot{x}e_c$		000	000	10K						

3. Smiths Industries Graphics Generator and Airborne Data General NOVA 3/12 Digital Computer (Figure V-13). This equipment provides the capability to generate display information formats for either head-up or head-down presentation. Complete programming flexibility permits an essentially unlimited range of calligraphic symbology and alphanumerics for the replication of any existing electronic format or the design of new ones. The computer is controlled from a remote miniature terminal in the cockpit (Figure V-14), so that any desired format can be selected in flight for presentation. The terminal can be placed in a horizontal position when not in use in order to minimize the visual obstructions.

4. Head-Up-Display (HUD) Unit (Figure V-15). This equipment is a Smiths Industries Pilot Display Unit (PDU), including CRT, optics and combining glass, mounted on a retractable mechanism above the instrument panel. The retraction arrangement provides the correct eye-to-glass distance for normal HUD viewing and quickly clears the PDU from the ejection envelope for flight safety.

5. Programmable Analog Symbol Generator (Figure V-16). For simpler display formats presented head-down, this unit can produce as many as 32 different calligraphic symbols. The desired format is selected in flight by ten (10) individual switches in the cockpit.

6. Head-Down Display (HUD) Unit (Figure V-17). This equipment is a Kaiser 5" CRT mounted in the instrument panel. It is currently driven by the analog symbol generator, but the capability may be expanded to include use of the programmable digital display generation equipment previously described.

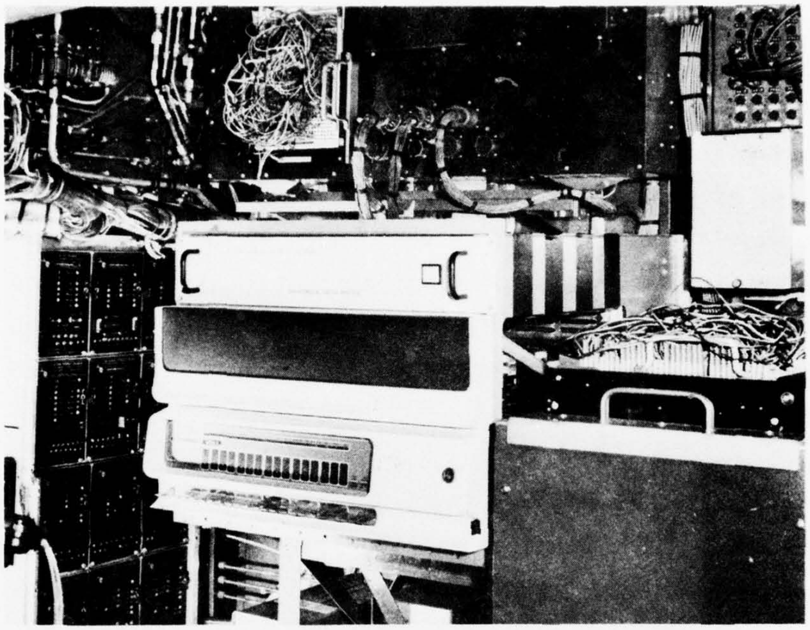


Figure V-13 PROGRAMMABLE DIGITAL DISPLAY EQUIPMENT

Figure V-14 COCKPIT COMPUTER TERMINAL

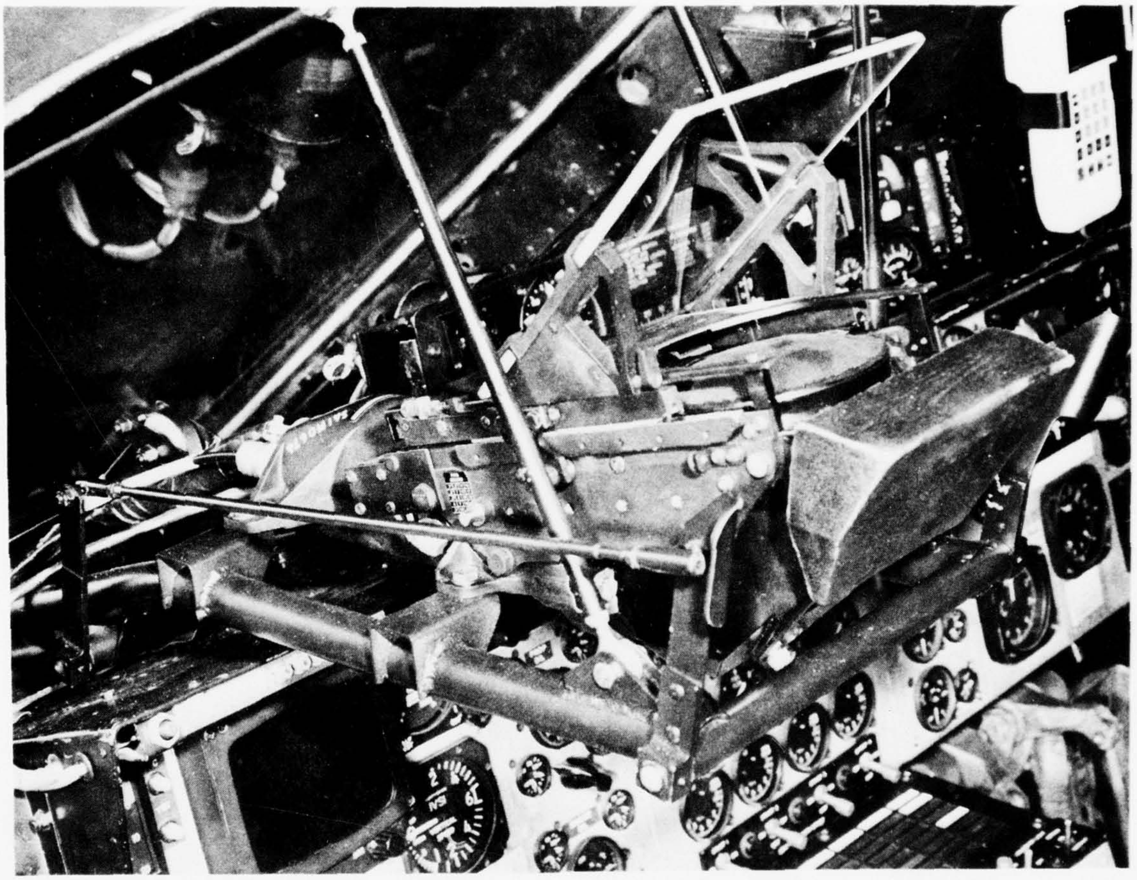


Figure V-15 HEAD-UP DISPLAY - VIEWING POSITION

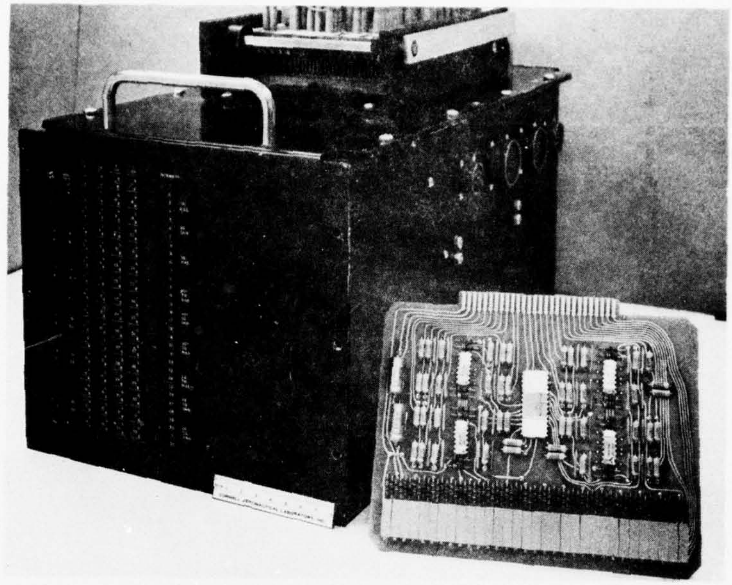


Figure V-16 PROGRAMMABLE ANALOG SYMBOL GENERATOR

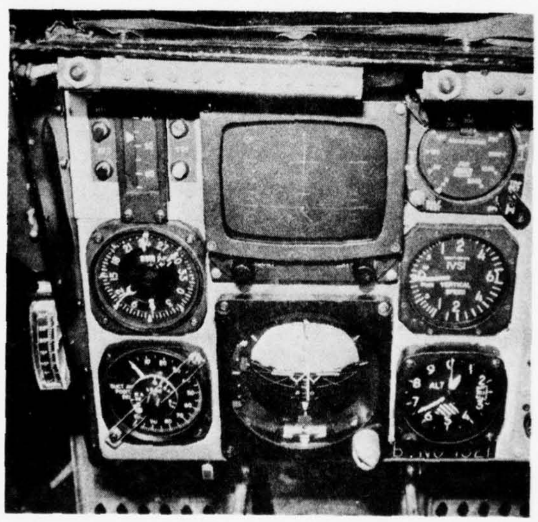


Figure V-17 HEAD-DOWN DISPLAY

DATA ACQUISITION AND PROCESSING SYSTEM - TELEMETRY VAN

Since the X-22A aircraft and variable stability system are extremely complex, requiring monitoring during flight of many more variables than can be easily scanned by the pilot, a versatile system for data telemetry, acquisition, and processing was designed for the X-22A.

All data pertinent to the flight of the X-22A aircraft are telemetered to a ground station via a pulse-code-modulated "L-band" telemetry link. Eighty channels are provided, with the data sampled at a 200 Hz rate and encoded into 9-bit words. Of these 80 channels, five are required for time and synchronization, one is subcommutated to 64 additional channels, and one more is required to identify the subcommutated channel. There are, then, 137 channels available for data transmission.

Patch panels in the X-22A aircraft permit selection of the 137 variables to be telemetered from approximately 200 that are available. For the research experiments, approximately 80 flight safety variables (such as bearing hanger vibration levels and various oil temperatures and pressures) are telemetered and monitored; the remaining 57 variables (such as angle of attack, stick control positions, and VSS electrical commands) are of interest to the flying qualities experiment.

The data are telemetered to a ground station and experiment control center housed in a mobile van (Figures V-18, 19). The van contains the following equipment:

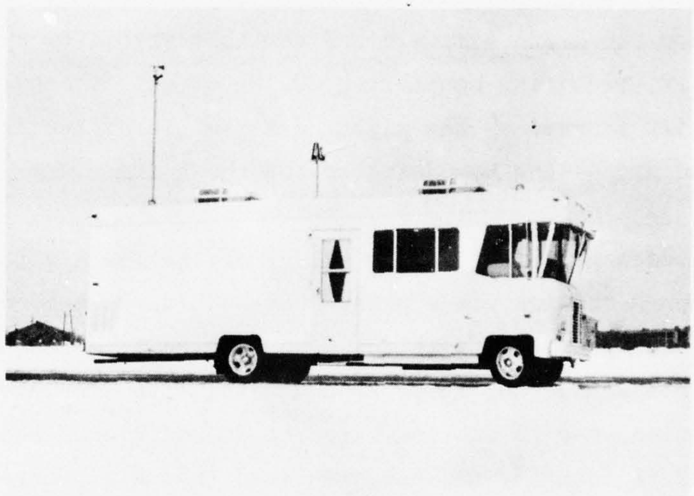


Figure V-18 MOBILE VAN, EXTERNAL VIEW

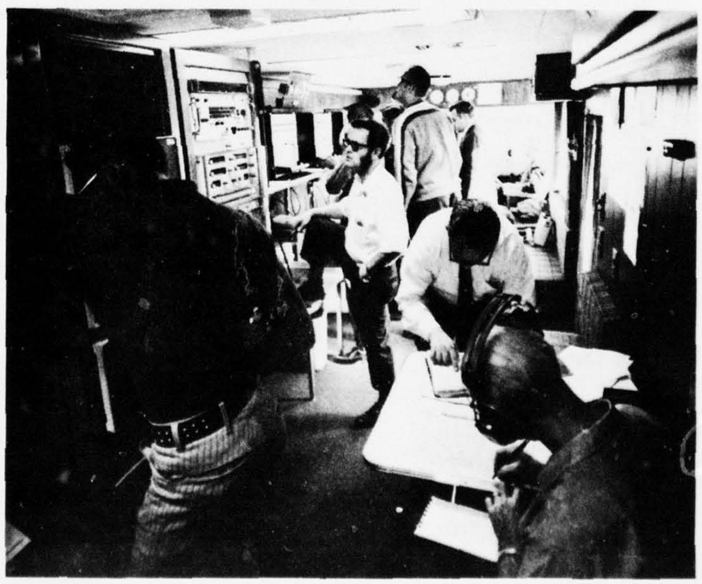


Figure V-19 MOBILE TELEMETRY VAN, INTERNAL VIEW

(a) an omnidirectional antenna and a steerable, directional antenna
(b) a telemetry receiver
(c) a PCM decommutator and signal simulator
(d) a tape recorder for recording the complete data stream
(e) a 32-channel digital-to-analog converter (DAC)
(f) four 6-channel chart recorders
(g) a panel of 9 meteres for continuous display of a fixed set of flight safety variables
(h) a patch panel to select a desired set of 32 variables for the DAC's
(i) a paper printer
(j) a mini-computer with 24K storage capacity, 800 nanosecond effective cycle time, 36 channels of Digital-to-Analog converters and 12 channels of Analog-to-Digital converters
(k) a teletypewriter
(l) a high-speed paper tape unit
(m) a 9-channel digital tape recorder
(n) a 360-channel VHF transceiver
(o) a voice-actuated magnetic tape recorder
(p) a weather station
(q) two 5 kW 115-volt, 60 Hz generators

A simplified block diagram of the functions of this equipment during a flight is shown in Figure V-20. The primary purposes of the equipment include flight safety monitoring, experiment control, and data processing, each of which is briefly described below.

Flight Safety Monitoring - High and/or low limit values for the variables are stored in a mini-computer; the telemetered data are processed through the computer on-line and compared continuously with these limits. In the event of a variable exceeding these preset limits, the teletypewriter unit immediately prints out the variable in question and its value. The high speed paper tape unit acts as an independent backup by printing out on command the values of all the telemetered variables.

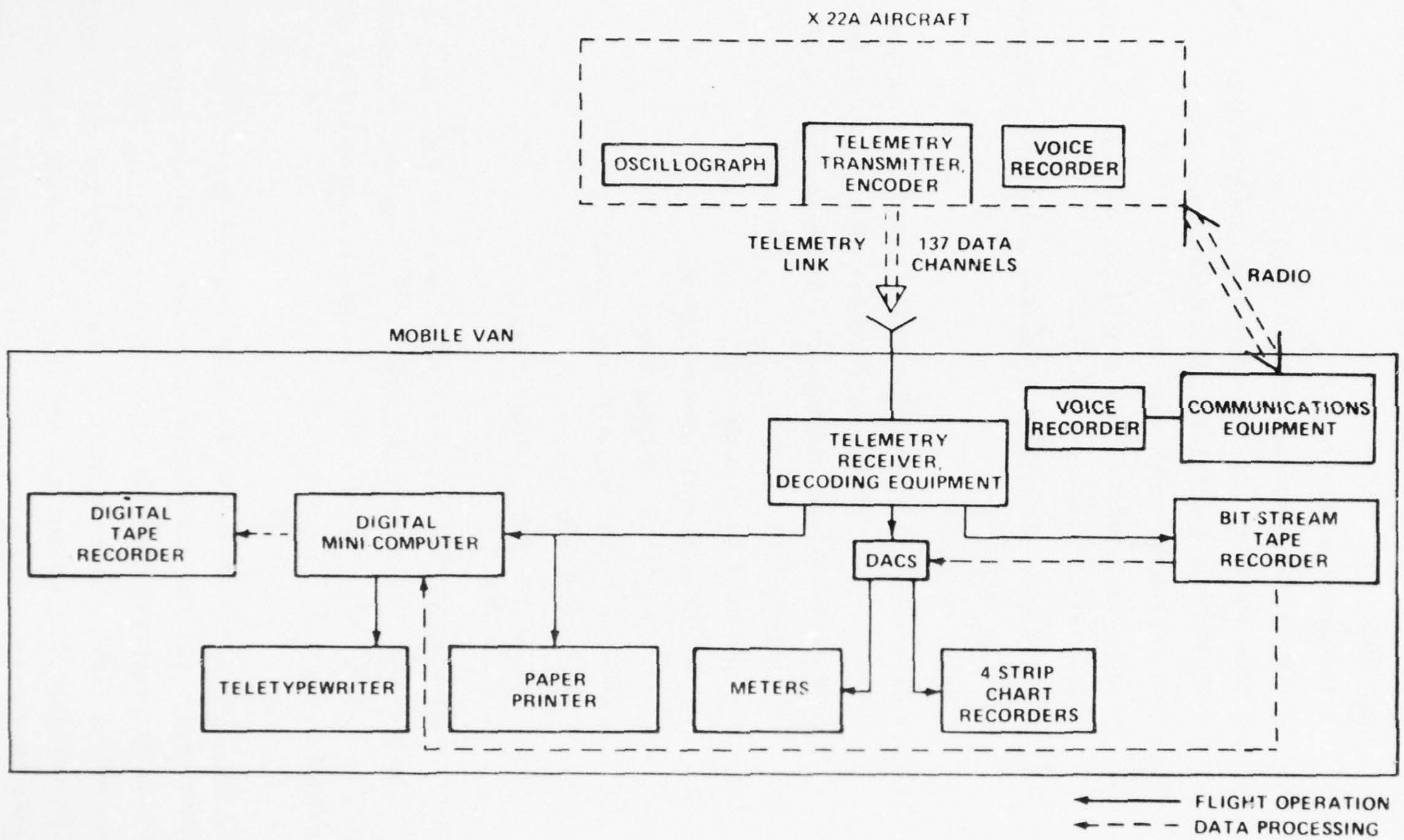


Figure V-20 SCHEMATIC DIAGRAM OF DIGITAL DATA ACQUISITION SYSTEM

Experiment Control - Pilot input and aircraft response variables are monitored on-line with four six-channel strip chart recorders.

Data Processing - The equipment in the van also serves to process the flight data digitally "off-line" after a flight. All telemetered data during a flight are recorded continuously on the bit-stream recorder. For digital data analysis, the appropriate portions of the appropriate channels are selected from the bit-stream recorder, and the format changed to be compatible with the IBM 370/165 computer used for the analyses. This is accomplished through use of the van computer and equipment to produce the required digital tape which is then processed by the IBM 370/165 computer.

MICROWAVE LANDING SYSTEM (MLS)

MLS Equipment

A summary description of the MLS is given at the end of this Appendix. Figure-21 shows the ground station equipment as typically set up and used during the X-22A Task IV Research Program flight Tests.

The standard MLS equipment, as described, was designed to produce error information and steering commands with respect to the localizer and a cockpit-selectable glide-slope. For the purposes of the X-22A flight research it was necessary to derive the position of the aircraft in an X, Y, Z coordinate system with the origin fixed in the MLS site. To accomplish this the airborne equipment in the X-22A was expanded to provide absolute elevation and azimuth information in addition to the normal error information.

The additional unit of airborne equipment developed for Calspan by Airborne Instrument Laboratories to provide the required data is visible as the black box at top right in Figure V-10. It contains the necessary digital-to-analog converters, serial to parallel converters, demultiplexers and associated power supplies. The analog output signals from this unit have the following characteristics:

AD-A068 818 CALSPAN CORP BUFFALO N Y F/G 1/3
AN EXPERIMENTAL INVESTIGATION OF CONTROL-DISPLAY REQUIREMENTS F--ETC(U)
JUL 78 J V LEBACQZ, R C RADFORD, J L BEILMAN N62269-76-C-0370
UNCLASSIFIED CALSPAN-AK-5985-F-1 NADC-76099-60 NL

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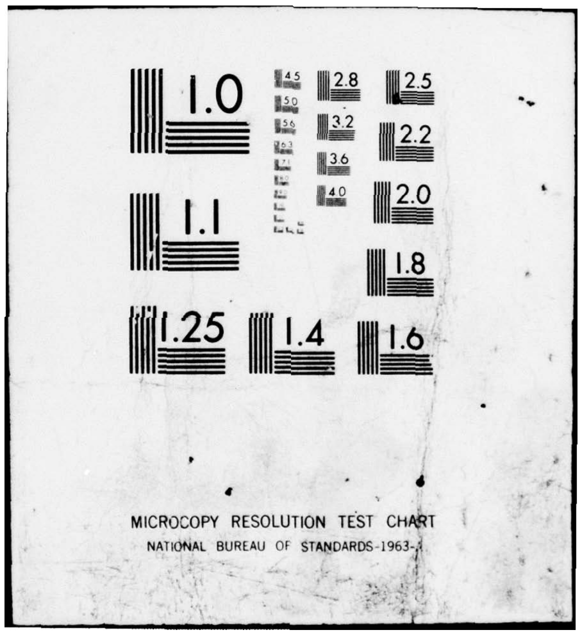
1.0
1.1
1.25
1.4
1.6
1.8
2.0
2.2
2.5
2.8
3.2
3.6
4.0
4.5
5.0
5.6
6.3
MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

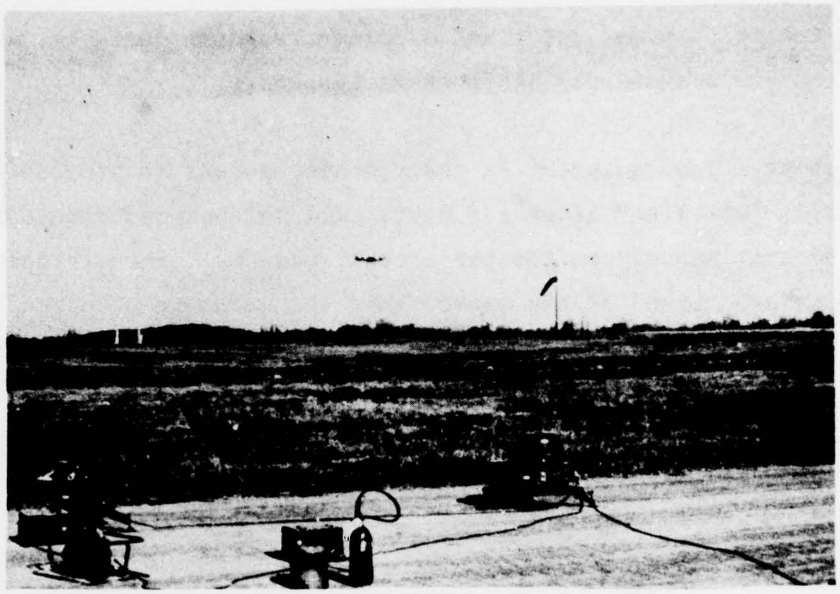

Figure V-21 MICROWAVE LANDING SYSTEM

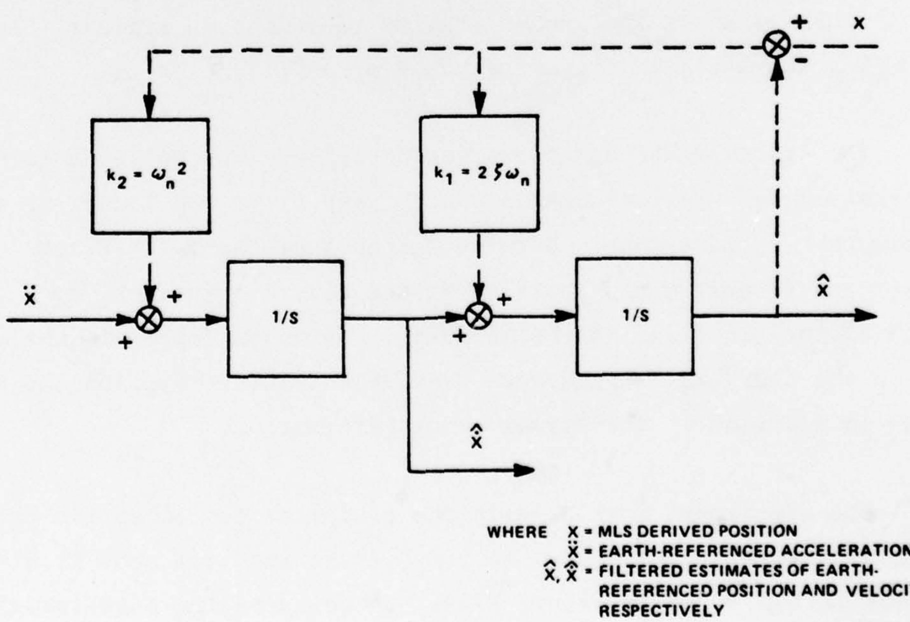

Figure V-22 MLS COMPLEMENTARY FILTER BLOCK DIAGRAM

Localizer: $\pm$ 10 VDC corresponding to $\pm 30^\circ$

Glide Slope: 0 to + 10 VDC corresponding to 0 to + 20°

DME : 0 to + 10 VDC corresponding to 0 to 10 n.mi.

The input signals, extracted from the AN/ARQ-31, are 12 bit plus sign digital words. The least significant bits of the angular data represent $1/64^\circ$ and the least significant bit of the distance data represents 15.17 feet.

MLS Signal Processing

It was desired to present the MLS data in X, Y and Z rectangular coordinates for both display and guidance generation. The exact equations to transform the MLS angular and range data to a rectangular coordinate system are complicated by the fact that the glide slope beam always lies in a plane which intersects the earth's surface on a line through the MLS site and perpendicular to the approach path. Thus the encoded elevation angle information from the MLS glide slope transmitter can only be precisely correct when the approaching aircraft is on the localizer. The elevation angle information will be in error by a factor ($1-\cos\epsilon$), where ϵ is the angular displacement of the aircraft from the localizer

If the localizer and glide slope units are not co-located, the exact equations become difficult to solve (Reference 38). It was desired to solve these equations on an analog computer, hence some simplifications were required. Both the glide slope and localizer were co-located and both binomial expansion and small angle assumptions were used to reduce the rectangular coordinate transformation to Equations (V-5), (V-6) and (V-7).

$$Xe = R\left(1 - 1/2\ \psi^2_{MLS} - 1/2\ \theta^2_{MLS}\right) \qquad \text{(V-5)}$$

$$Ye = R\,\psi_{MLS}\left(1 - 1/2\ \theta^2_{MLS} - 1/6\ \psi^2_{MLS}\right) \qquad \text{(V-6)}$$

$$Ze = R\ \theta_{MLS}\left(1 - 1/2\ \psi^2_{MLS}\right) \qquad \text{(V-7)}$$

The rectangular coordinate errors resulting from the approximations are small (See Table V-3). The errors are a maximum for large elevation and azimuth angles. However, the nature of the approach and localizer acquisition tends to preclude both angles being large simultaneously. When the localizer error is large, the aircraft is at a relatively great distance from the MLS site (small elevation angle). Since the pilot minimizes the localizer error fairly rapidly, that error tends to remain small as the elevation angle increases to its maximum value - the glide slope.

TABLE V-3

MLS RECTANGULAR COORDINATE TRANSFORMATION APPROXIMATION ERRORS

θ_{MLS} DEG	ψ_{MLS} DEG	Ex %	Ey %	Ez %
20	30	1.4	0.6	1.4
5	10	0.4	0.003	0.1
2.86	0	0.006	0	0.9
0	0	0	0	0

where X = longitudinal distance to the MLS site

Y = lateral displacement from the MLS site

Z = altitude above the MLS site

R = MLS slant range

θ_{MLS} = MLS elevation angle

ψ_{MLS} = MLS azimuth angle

Accurate position and velocity information with low noise content is required for instrument approaches, for both control and display applications. The MLS data is used to derive earth referenced range (X, Y, Z) and velocity ($\dot{X}$, $\dot{Y}$, $\dot{Z}$) information. Multipath in the RF link and digital filtering within the airborne receiver can produce a low-frequency noise component. Twelve-bit digital-to-analog converters are interfaced to the MLS digital data output. The data is truncated at the low end to accommodate the twelve-bit words. Therefore, the minimum resolution of the elevation (θ_{MLS}) and azimuth (ψ_{MLS}) data is 1/64 of a degree and the minimum resolution of range (R) is 15.17 feet. The elevation azimuth and range data will change in discrete steps equivalent to the minimum resolution. The MLS is a sampled data system with an update rate determined by the antenna scan rate which is 4 samples per second. Velocity information cannot be obtained by differentiation of the MLS data without resultant noise and unacceptable time lags if only simple fitering is used to reduce the noise.

The MLS derived rectangular position data was blended in complementary filters with inertial data to provide smooth estimates of earth-referenced position and velocity. The inertial data was obtained from body axis accelerometer signals transformed into earth-referenced accelerations. The basic design approach of the complementary filters is described in Reference 39. Figure V-22 is a block diagram of the MLS complementary filter and Figure V-23 is a diagram of the analog computer programming of this filter. The equations for the complementary filters are given in Equations (V-8) and (V-9).

$$\hat{\dot{x}} = \frac{(s + k_1)\ddot{x} + k_2 s x}{s^2 + k_1 s + k_2} \qquad \text{(V-8)}$$

$$\hat{x} = \frac{\ddot{x} + (s k_1 + k_2) x}{s^2 + k_1 s + k_2} \qquad \text{(V-9)}$$

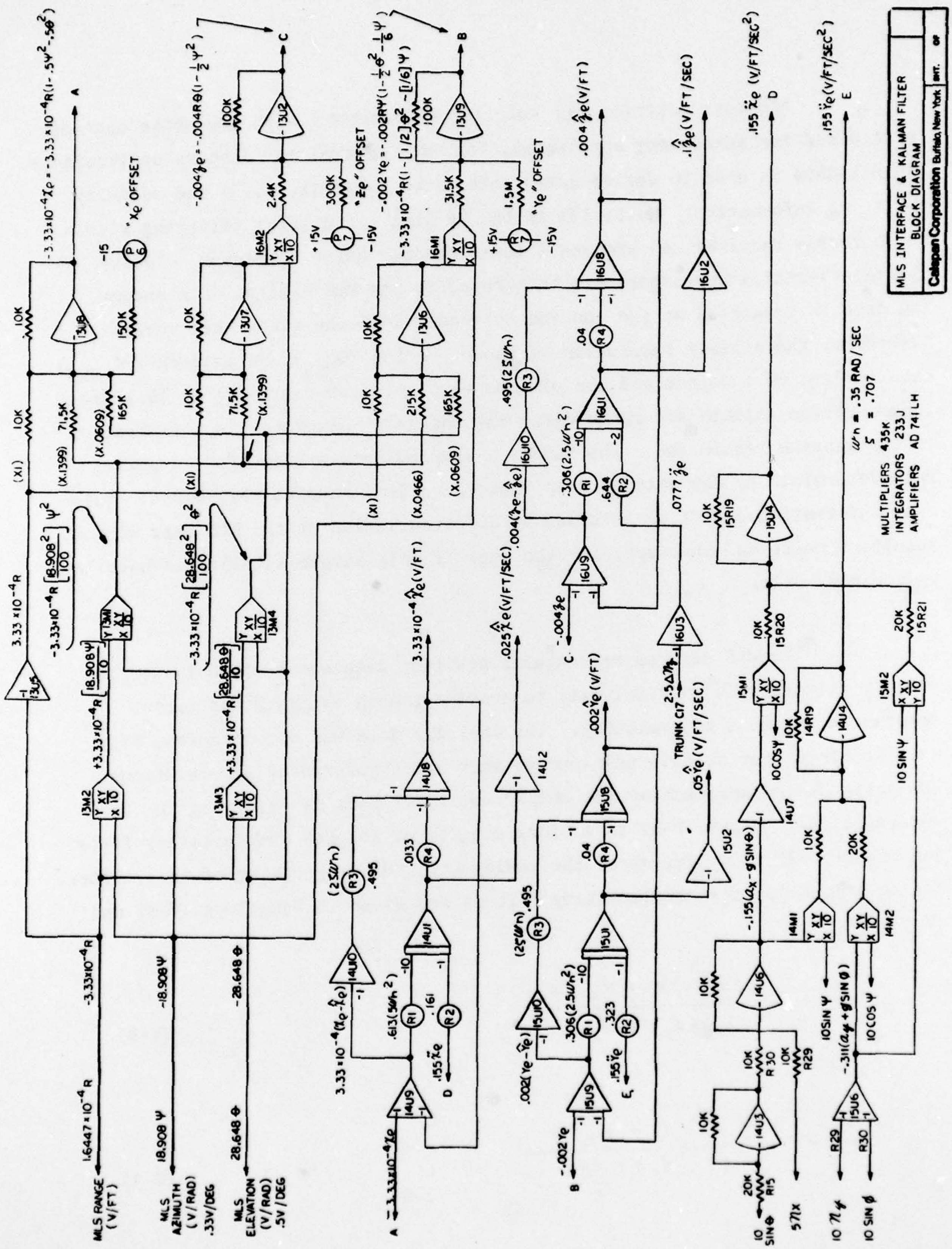

Figure V-23 BLOCK DIAGRAM FOR MLS INTERFACE AND KALMAN FILTER BLOCK DIAGRAM

where $k_1 = 2\zeta\omega_n$

$k_2 = \omega_n^2$

ζ = damping ratio

ω_n = undamped natural frequency

x = MLS derived position information

$\ddot{x}$ = earth referenced acceleration

$\hat{x}$ = filtered estimate of position

$\hat{\dot{x}}$ = filtered estimate of velocity

The choice of the filter constants is described in Reference 39. The damping ratio is a constant selected as $\zeta = 0.7$ and the undamped natural frequency (ω_n) is selected as the square root of the ratio of accelerometer noise to position noise. The filter natural frequency chosen was $\omega_n = .35$ rad/sec. This selection was verified empirically and the resultant filtered position and rate estimate for the longitudinal axis are presented in Figure V-24.

AN/ARQ-31 U. S. Army Tactical Landing System Airborne Set

The AN/ARQ-31 is the advanced capability microwave scanning beam landing system airborne set that has been developed to meet the needs of the U. S. Army.

The fullest potential of a microwave scanning beam landing system is achieved when the airborne receiving equipment is capable of responding with equal accuracy and linearity anywhere within the entire coverage sector of ground station transmissions and when distance from the ground equipment is also available in the aircraft. The AN/ARQ-31, airborne set for the U. S.

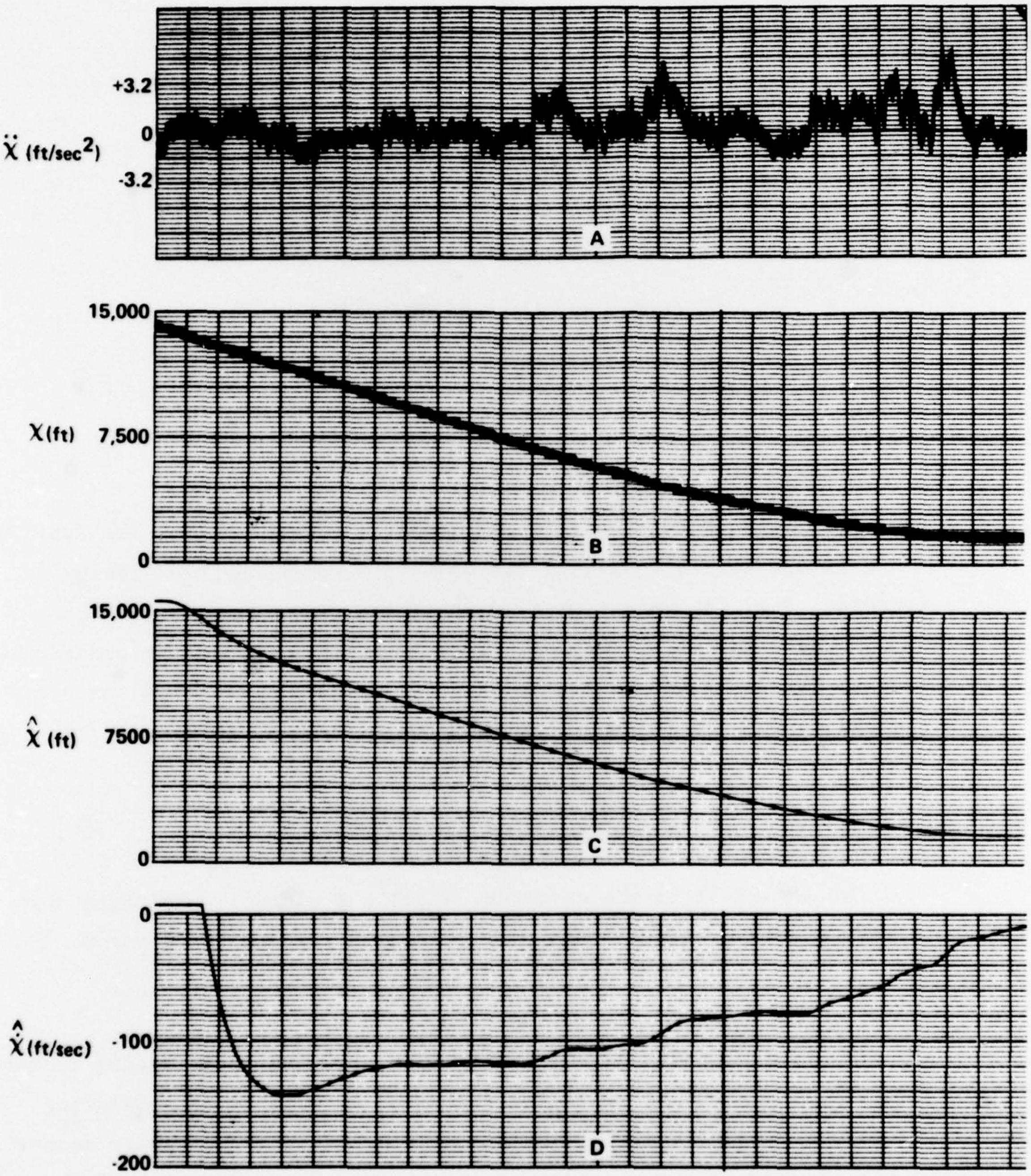

Figure V-24 MLS COMPLEMENTARY FILTER INPUTS AND OUTPUTS

Army Tactical Landing System, provides this type of complete capability. Deviation voltages for driving flight control or display equipment are derived after the angle information is fully decoded; consequently, there are no limitations in this type of receiver as to choice of flightpath angle or to course sensitivity (degrees for full-scan deflection).

An AN/ARQ-31 includes a decoder-receiver, a distance measuring transmitter, and a control unit. An antenna and a set of indicators especially developed for U. S. Army field evaluation are also included.

The AN/ARQ-31 Ku-band precision DME interrogator transmitter is a separate unit that can be included as an option. The decoder-receiver unit can function independently as a localizer and glideslope angle only receiver.

The receiver unit of the AN/ARQ-31 is a digital signal processor from the IF amplifier to the output circuits. All information developed is in digital form with digital-to-analog conversions made only to satisfy the requirements of standardized flight control and display equipment. The digital computation capability provides outputs for height (based on elevation and distance) and range rate (based upon differentiation of the DME derived range). The standard outputs are the normal voltage analog of glideslope and localizer course deviations. Slant range from the DME ground station is provided as an analog output for the fine range 0-6000 ft. and as a digital output per ARINC Characteristic 568 for the course range (0-20 mi.). All output functions have associated flag outputs that indicate any departure from normal operation.

A PUSH-TO-TEST button on the control unit provides a built-in-test capability to isolate faults to the defective unit. A subassembly test set (TS-3379/ARQ-31) and module tester (TS-3380/ARQ-31) have also been developed for the Army's maintenance shops.

AN/ARQ-31 SPECIFICATIONS

Status	Development Test/Operational Service Test Models. Product designs ready for off-the-shelf delivery.
Dimensions	Decoder-Receiver: 22 cm (8½") H × 13 cm (5") W × 46 cm (18") D Distance Measuring Transmitter: 18 cm (7") H × 9 cm (3½") W × 29 cm (11⅜") D Control Unit: 8 cm (3") H × 15 cm (5¾") W × 12 cm (4⅝") D
Weight	Decoder-Receiver: 7.7 kg (17.0 lbs) Distance Transmitter: 2.7 kg (6.0 lbs) Control Box: 0.5 kg (1.2 lbs)
Glideslope Angle	Air selectable 1-degree increments (3 to 12 degrees)
Input Power	Decoder-Receiver: +22.5 to 28.5 Vdc, 78 W Distance Measuring Transmitter: +22.5 to 28.5 Vdc, 22 W MIL-STD-704 Category B
Frequency Band	15.4 to 15.7 GHz
Channels	Air selectable; 1 of 10 crystal-controlled channels
Sensitivity	−76 dBm (tracking level)
Range	30 nmi in clear weather, 10 nmi in 10 mm/hr rainfall
Data Rate	Dependent on ground system
DME Interrogation Rate	300 interrogations/second during 110-ms DME period
Antenna Polarization	Horizontal (vertically polarized antennas available also)
Environment	MIL-E-5400, Class 1A (−57 to +71°C)
Angle Outputs	150 μA per 1000-ohm load for full scale deflection (3 loads)
Linear Deflections	Variable — dependent upon glideslope angle selected by pilot. Both glideslope and localizer linear full scale range increases as glideslope angle is increased. Glideslope Range: ±1 to ±4 degrees Localizer Range: ±2 to ±5 degrees
Signal Characteristics	Pulse repetition period (60 μs = 0 degree, 1 μs/degree sensitivity)

The AN/ARQ-31 control unit provides for the selection of any one of 10 RF channels and selection of glideslope angle in 1-degree steps from 3 to 12 degrees.

The AN/ARQ-31 has been constructed to strict military specifications under a full U. S. Army development program. The equipment employs solid-state components throughout (except for the Ku-band DME transmitter tube). Digital packaging uses dual-in-line integrated circuits, double sided PC boards, and a multilayer mother board. Compliance with severe EMC specifications (MIL-STD-461, Notice 4 and MIL-STD-462, Notice 3) assures the highest level of RF performance with minimum interference effects.

AN/TRQ-33 U. S. Army Tactical Landing System Ground Set

The AN/TRQ-33 U. S. Army Tactical Landing System Ground Set is a lightweight portable microwave scanning beam equipment that embodies all the features required to provide the most advanced landing guidance techniques for helicopter or fixed wing aircraft. This fully military qualified follow-on to the exploratory A-SCAN equipment embodies the ruggedness and reliability needed for rough field operations.

The AN/TRQ-33 consists of a localizer, glideslope, an optional Ku-band precision DME module, field monitors, and a remote control unit. The DME module can be attached to either the localizer or glideslope. The basic units use 24-Vdc power inputs from batteries. In addition, separate power supplies allow the use of a wide range of ac prime power or 28-Vdc generators. The remote control unit provides the capability to turn the equipment on or off and to monitor its status from a point that is remote from the glideslope and localizer units.

The AN/TRQ-33 antennas rotate under weatherproof radomes providing ±30 degrees of azimuth coverage and elevation coverage up to 20 degrees. The 2-degree beamwidth glideslope antenna provides precision approach paths down to glideslope angles of 3 degrees with sufficient under course coverage to provide specified accuracy to at least 1 degree below the lowest selectable glideslope angle.

Leveling and alignment fixtures and procedures allow for rapid siting of the equipment at nonpermanent locations. All terrain pads are included on the folding and adjustable legs.

The AN/TRQ-33 has been designed to the most sophisticated military maintenance specifications. Built-in test and fault location are included. Field procedures allow the unskilled operator to determine the location of a fault in a major subunit that can be field replaced. A system test set (the TS-3381/TRQ-33) and a module tester (the TS-3382/TRQ-33) have also been developed for maintenance shops.

The AN/TRQ-33 is solid-state except for the long-life magnetron transmitting tubes. It features a turnable magnetron which can be set on channel without use of test equipment.

AN/TRQ-33 (XE-1) SPECIFICATIONS

Status	Development Test/Operational Test Models. Product designs ready for off-the-shelf delivery
Dimensions	Localizer Group • Height on Site: 89 cm (35") • Foot Pad Triangle: 127 cm (50") × 104 cm (41") × 104 cm (41") • Stored Volume: 97 cm (38") W × 86 cm (34") D × 71 cm (28") H Glideslope Group • Height on Site: 105 cm (41.5") • Foot Pad Triangle: 109 cm (43") × 89 cm (35") × 79 cm (31") • Stored Volume: 84 cm (33") W × 86 cm (34") D × 91 cm (36") H DME Unit: 22 cm (8.5") W × 30 cm (12") D × 33 cm (13") H
Weight	Localizer Group: 50 kg (110 lbs) Glideslope Group: 53 kg (116 lbs) DME Unit: 10 kg (23 lbs.)
Power Input	20 to 31 Vdc, 200 W Localizer, 200 W Glideslope, 50 W DME
Frequency Band	15.4 to 15.7 GHz
Channels	10 RF can be set in field
Coverage	Localizer Group: ±30 degrees (60 degrees total sector) Glideslope Group: 0 to 20 degrees DME Unit: 60 degrees azimuth 20 degrees elevation
Range	30 nmi in clear weather, 10 nmi in 10 mm/hr rainfall (—71 dBm receiver sensitivity)
Setup Accuracy	Localizer Group: ±0.1 degree (on axis) Glideslope Group: ±0.1 degree (on axis)
Angle Accuracy	Bias 0.1 degree, noise 0.05 (2 sigma)
DME Accuracy	±0.05 μs (turnaround delay)
Data Rate	4 Hz
Scan Rate	4 scans/sec.
Antenna Beam-widths (3 dB)	Localizer: 3-degree azimuth, cosecant to 20-degree elevation Glideslope: 60-degree azimuth, 2-degree elevation DME: 60-degree azimuth, 20-degree elevation
Antenna Gain	Localizer: 27 dB Glideslope: 23 dB DME: 16 dB
Polarization	Horizontally polarized (vertically polarized antennas available also)
Transmitter Power	2 kW peak
Environmental Specifications	Drop shock, vibration, immersion, dust, salt-fog, fungus, rain, and wind Temperature range: —46 to +52°C
Monitors	Internal on all functions. Fault locatior, single point field monitor. (Automatic shutdown for out of tolerance signals)

X-22A GROUND SIMULATOR

The fixed-base X-22A ground simulator (Figure V-25) is designed to supplement the X-22A aircraft operation in the following manner:

- Perform preliminary tests of experimental programs prior to flight tests in the actual aircraft.
- Develop new experimental hardware and systems, such as control systems and displays prior to installation in the actual aircraft.
- Ground test new equipment and check experimental setups for the aircraft prior to actual flight test.
- Provide pilot training as required.

The ground simulator is composed of the following functional components:

- Digital computer - solves the computer model equations (housed in X-22A mobile van).
- Variable feel system - provides force-position characteristics for pilot's stick and rudder pedal controls.
- Variable stability system electronics - combines inputs from pilot's controls with feedback of computed responses to provide control inputs to computer model.

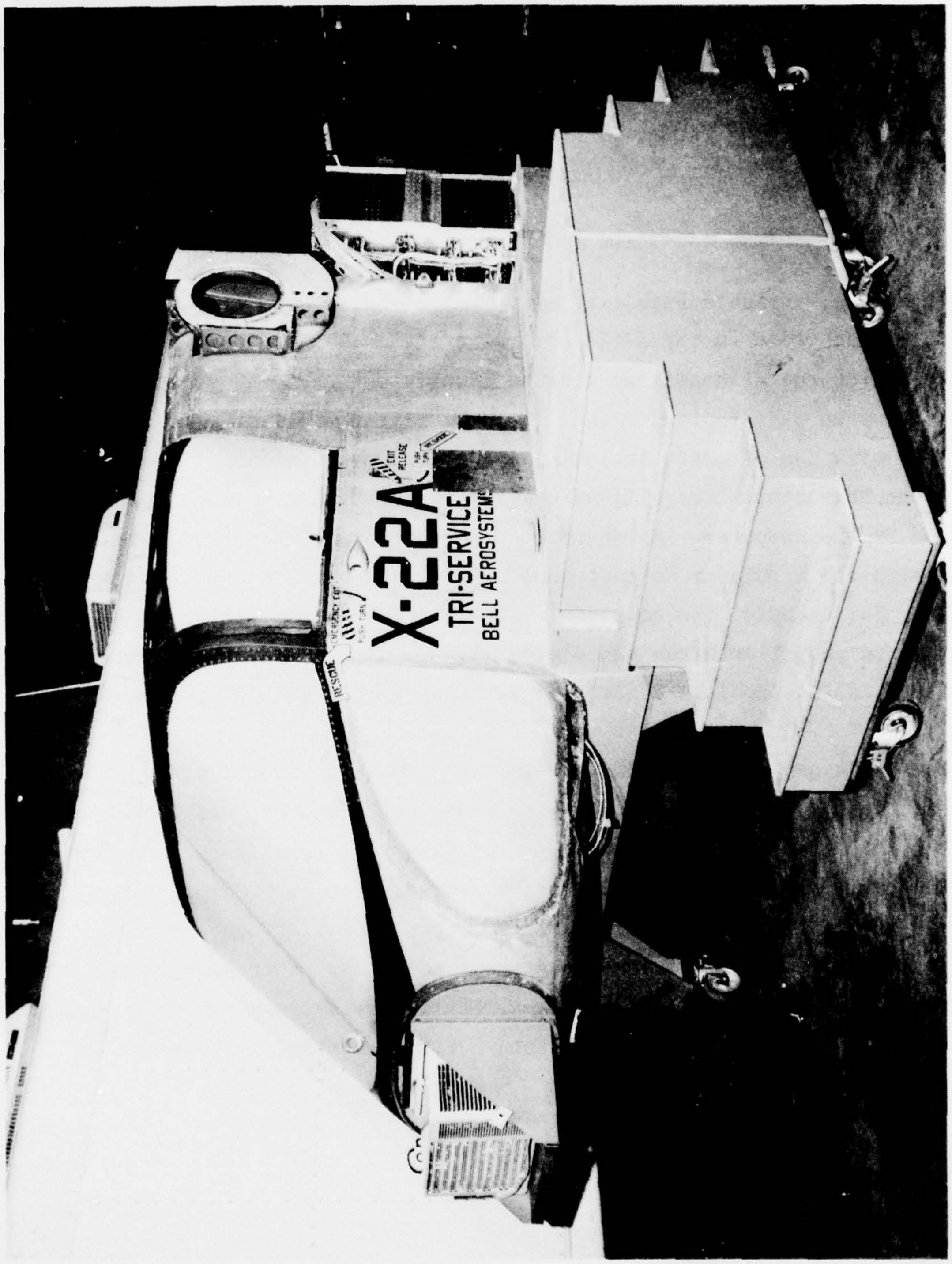

Figure V-25 X-22A GROUND SIMULATOR

- Cockpit displays - flight instruments used by pilot to fly under instrument conditions (including CRT).

- Interface - patch boards, signal conversion, filtering, and scaling between simulator components.

The feel system, variable stability system electronics, and flight instruments duplicate those found in the X-22A aircraft; the analog and digital symbol generators from the aircraft may also be readily moved to the simulator to provide the same CRT displays investigated in flight. All other elements associated with the aircraft including its airframe equations of motion, power plant characteristics, flight control system, and guidance system are simulated by the computer. As an option, the actual X-22A aircraft can be tied in with the simulator so that some of its components can be incorporated directly. For example, the complete flight control system can be employed with measured propeller blade and elevon signals used as inputs to the computer model for studying problems associated with the flight control system itself.

The X-22A ground simulator can also be used as a general aircraft instrument flight simulator. The use of a digital computer, with complete programming flexibility and tape storing of programs, greatly enhances the capability of the ground simulator for general simulation. Complex and nonlinear aerodynamic characteristics for either V/STOL or conventional aircraft can be readily incorporated, as can nonlinear control characteristics, or simple linearized equations of motion. Auxiliary systems, such as approach systems or a sophisticated digital adaptive flight control system, can be readily included in the simulation.